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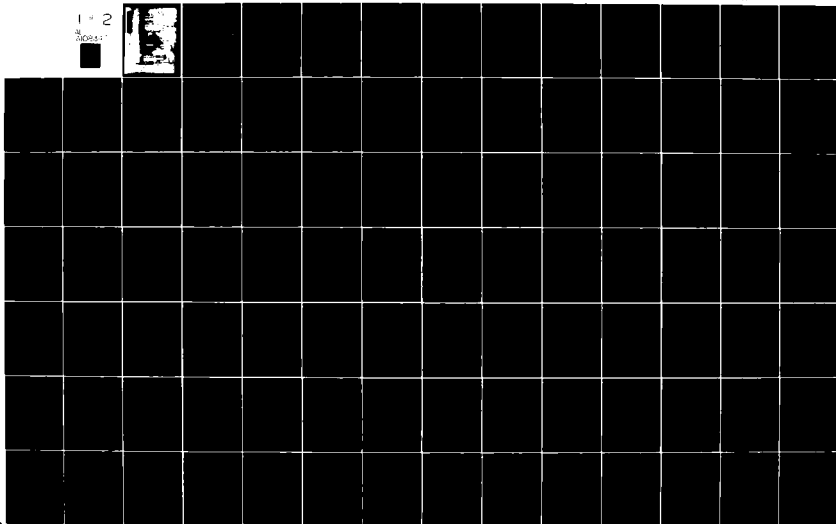
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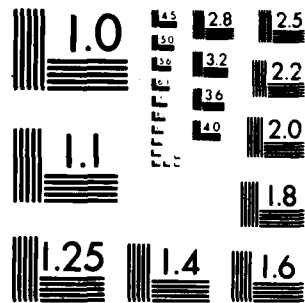
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JOINT SERVICES ELECTRONICS PROGRAM
ANNUAL PROGRESS REPORT (CONTRACT F49620-79-C-0178)

1 September 1980 - 31 August 1981

by

D.J. Angelakos

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An annual report of the JSEP (Joint Services Electronics Program) in Electromagnetics, Solid State Electronics, Materials and Devices, Quantum Electronics and Information Sciences is presented. In addition, results of the research to date are summarized and significant accomplishments are indicated.		

1. INTRODUCTION

During the period 1 May 1981 through 30 April 1982, the Electronics Research Laboratory (ERL), University of California, Berkeley, is receiving support for its basic program from the Joint Services Electronics Program (JSEP), sponsored by the Departments of the Air Force (Air Force Office of Scientific Research), Army (Army Research Office), and Navy (Office of Naval Research), under contract F49620-79-C-0178.

This annual report is an updating report; hence it covers the period 1 September 1980 through 31 August 1981. Significant Accomplishments, where applicable, appear in the project reports (section A). In particular, the three most significant accomplishments, as determined by the Director, are summarized as:

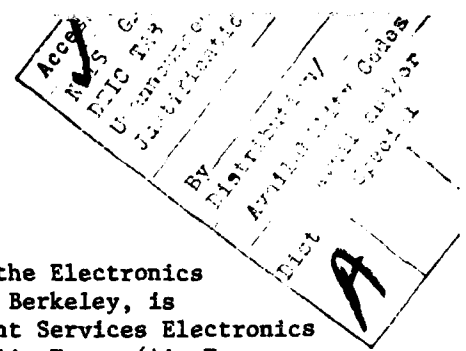
i. Project SSD-82-3 - New Techniques for Wide-Dynamic-Range Signal Processing Using Monolithic Integrated Circuit Technology

(a) A new high-frequency bipolar monolithic process has been devised and extensively characterized for both low-frequency and high-frequency parameters. This research has led to new circuit configurations for high-frequency monolithic filters, switches and amplifiers which are currently being fabricated.

(b) A new chopper stabilized differential filtering technique was developed, and a monolithic prototype fabricated. This prototype has been extensively characterized, demonstrating dynamic range and power supply rejection performance well beyond any previously published levels. An extensive theoretical analysis of the sources of noise in switched capacitor filters has been carried out, resulting in a better understanding of the fundamental limitations on dynamic range as a function of energy storage element values. These results have been subsequently applied to the bandpass case, with important conclusions regarding the dynamic range of high-Q bandpass filter structures.

ii. Project QE-82-2 - Millimeter and Infrared Heterodyne Mixing and Detection

A major effort in the past was devoted to a study of the mode-stability problem in semiconductor lasers, and our work was summarized in an invited paper, "Control of Mode Behavior in Semiconductor Lasers" published in IEEE J. Quantum Electron. In brief, we showed that a lateral index difference as small as 10^{-3} should be sufficient to stabilize the lateral mode. Many laser structures, including the IRW laser, the CJSF laser, and the DCC-CSP laser developed in our laboratory satisfy this index-difference requirement. We also demonstrated in the experiment with the DCC-CSP laser and the TEPOSE laser (see publication J. Appl. Phys., 52, 614, 1981) the importance of a uniform and symmetric carrier distribution. It is essential to keep any carrier-density variation below 10^{17} cm^{-3} in order to maintain lateral-mode stability in weakly index-guided lasers.



A

INTRODUCTION - continued

iii. Project ISS-82-1 - Large-Scale and Nonlinear Circuits Study

A new algorithm has recently been developed for solving piecewise-linear equations of nonlinear electronic circuits.* Unlike other methods, this algorithm guarantees that all solutions will be found in a finite number of steps. The method depends crucially on the above cited developed which allows a multi-dimensional piecewise-linear function to be represented in a closed canonical form. This highly compact representation requires only a minimum amount of computer storage and is responsible for the efficiency of the algorithm.

The report contains:

- A. 1981-1982 JSEP Projects: as of 31 August 1981
- B. Consolidated List of JSEP Published Papers and Memorandums through 1 May 1979.

During this time period 1 September 1980 - 31 August 1981, there are currently an additional 14 Journal papers being processed: in press, in review, submitted and being prepared. Further, there have been 16 Conference papers presented (or to be presented).

* L. O. Chua and Robin L-P. Ying, "Finding all solutions of piecewise-linear equations," ERL Memo UCB/ERL M81/54, 23 July 1981.

2. RESEARCH PROJECTS

A. 1981-1982 JSEP Projects: as of 31 August 1981

Project No.	Project No.	Title	Investigator(s)
I. <u>ELECTROMAGNETICS</u>			
EM-82-1		→ Electromagnetic Scattering by Multiple Targets and Targets in Multiple Media,	D.J. Angelakos K.K. Mei
EM-82-2		Millimeter Wavelength Electromagnetic Structures	S.F. Schwarz K.K. Mei D.J. Angelakos
II. <u>SOLID STATE ELECTRONICS</u>			
A. <u>Materials</u>			
SSM-82-1		→ Hot-Electron Injection and Trapping at Si/Insulator Interfaces,	C. Hu R.S. Muller
SSM-82-2		III-V Compound Semiconductors; Material Property and Device Studies	S. Wang C. Hu
SSM-82-3		→ Molecular Beam Epitaxy and Its Applications to Studies of Materials Aspects of Microstructure Engineering;	S. Wang N. Cheung
B. <u>Devices</u>			
SSD-82-1		Critical Problems in Lithography and Their Impact on Practical Performance	A.R. Neureuther W.G. Oldham
SSD-82-2		→ Study of Effects Limiting Realization of Far-Submicron Superconductive Electronic Structures;	T. Van Duzer
SSD-82-3		New Techniques for Wide-Dynamic-Range Signal Processing Using Integrated Circuit Technology	R.W. Brodersen P.R. Gray R.G. Meyer D.O. Pederson

RESEARCH PROJECTS - continued

<u>Project No.</u>	<u>Title</u>	<u>Investigator(s)</u>
II. <u>SOLID STATE ELECTRONICS</u>		
B. <u>Devices (cont.)</u>		
SSD-82-4	Research on Electronic Systems Composed of Polymer Films and Planar Si Devices for Transducer Applications	D.W. Hess R.S. Muller
III. <u>QUANTUM ELECTRONICS</u>		
QE-82-1	Functional Analysis of Novel Semiconductor Lasers for an Integrated-Optical-Network Viewpoint	J.R. Whinnery S. Wang
QE-82-2	Millimeter and Infra-red Heterodyne Mixing and Detection, <i>dir</i>	T.K. Gustafson S.E. Schwarz T. Van Duzer
IV. <u>INFORMATION SYSTEMS</u>		
ISS-82-1	Large-Scale and Nonlinear Circuits Study	L. O. Chua E. S. Kuh
ISS-82-2	Control of Large Sytems	C.A. Desoer P.P. Varaiya
ISS-82-3	Computer Optimization of Electronic Circuits	A. Sangiovanni-Vincentelli R.G. Meyer E. Polak

B. Consolidated List of JSEP Published Papers and Memorandums through 31 August 1981.

A. 1981-1982 JSEP PROJECTS:

AS OF 31 AUGUST 1981

University of California

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

I. Basic Research in Electromagnetics

Coordinator: Professor K. K. Mei

Basic research in electromagnetics at ERL presently consists of two parts. One is the development and application of computational techniques to electromagnetics, and the other is the basic research in theory and experimentation of electromagnetics at submillimeter wavelengths. These two research activities are described in the following.

Computations in Electromagnetics

Research in electromagnetic theory was traditionally done within the regime of applied mathematics. Since the advent of high speed digital computers, we have seen more and more emphasis on the computational research being done in applied electromagnetics. In the early 1960's the main thrust of electromagnetic related computation was in integral equation approaches¹. The integral equation was a natural choice in radiation problems because the radiation conditions at infinity could easily be satisfied by using proper Green's functions. Although the integral equation method is not too well adapted to problems involving fat bodies and dielectric bodies, early investigators were still quite happy with it, because even with its limitations it was possible to solve many problems which were hitherto unsolvable. As more and more problems were solved, researchers began to look for alternatives to the integral equation approach, which might be better than the integral equation method in solving fat, dielectric or even inhomogeneous bodies. This effort is represented by the unimoment method which was developed by K.K. Mei and his associates at ERL², and the several publications that follow^{3,4} indeed show that the differential equation approach can be very efficient in regions where the integral equation method is clumsy and impractical. This method is currently being used to investigate the scattering by buried dielectric obstacles, a project now supported outside the JSEP.

The unimoment method is not only good in solving scattering by dielectric bodies, it is also an excellent technique for solving scattering by perfectly conducting bodies. A simple illustration shows how it works. Consider the scattering by a conducting spheroid. Outside a circumscribing sphere, the solution is expressed in classical spherical harmonics with undetermined coefficients, and inside the sphere the solutions are generated by solving the finite element equations. The expansion coefficients on both sides of the sphere are determined by enforcing the continuity conditions on the sphere. It is interesting to see that the finite element mesh area becomes larger if the spheroid becomes thinner, and it becomes smaller if the spheroid becomes fat. That means the unimoment method is efficient (more precise) for a fat scatterer than a skinny scatterer. The integral equation methods work just the opposite way, i.e., the surface area of the scatter increases as the scatter becomes fatter and hence requires more computation.

We have already succeeded in using the unimoment method to solve scattering by dielectric bodies⁵, and it is apparent that it should work even better when applied to a single fat metal scatterer. We have also completed two-body scattering involving two metal scatterers^{7,8}.

Other applications of our computational skill are considerable, but we only wish to investigate fundamental problems. One of the fascinating problems is that of the infrared and optical antennas. At optical frequencies the material behaves very differently from its known properties at microwave frequencies. The computational skill we have developed for dielectric bodies can be used to obtain physical insight into the operation of infrared antennas. It will be used to verify experimental observations and to provide design data to improve such antennas.

The scattering by two bodies of different shapes has been shown to be successful. The results are now available^{7,8}. Although we have contributed a lot of effort to the unimoment method, we will still be actively involved with the method of moment. In particular, we will be investigating wire antennas or scatterers which are partially buried in a lossy ground.

Electromagnetics at Submillimeter Wavelengths

Radio, microwave, submillimeter wave and light are all electromagnetic waves. The only difference between them is the frequency. However, both in theory and application they are dealt with quite differently. For example, the guided transmission of radio is mostly by coaxial lines, of microwave by metal waveguides, and of light by beams or dielectric waveguides. There are borderline frequencies where different transmission methods can be used. That indeed is the case at submillimeter waves to low infrared waves.

Under the previous sponsorship of JSEP we investigated both metal and dielectric structures such as antennas and wave guides at low infrared frequencies. It has turned out that the metal guide, while lossy, is an excellent device to concentrate electromagnetic power to a very small region, much less than a wavelength. The bulk of any submillimeter device has to consist of dielectric material as antennas and guides. Hence, our effort for the next period will emphasize the application of dielectric guiding structures and couplers at mm waves.

References

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: EM-82-1

Last Year's No.(s): EM-81-1

Title: Electromagnetic Scattering by Multiple Targets
and Targets in Multiple Media

Senior Principal Investigator(s): D. J. Angelakos
K. K. Mei

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642-4106

Scientific Objective

Multiple scattering of conducting and dielectric (or combination thereof) bodies is a problem of both academic and practical interest, as is the problem of scattering in multi-media environment. The knowledge of multi-body and multi-media scattering will help many design techniques in microwaves; it may also provide insight into many physical phenomena in field theories. However, scattering by electromagnetic wave is a difficult problem even without the complication of multiple scattering. Recent development of the Unimoment Method has advanced the art of scattering-related computation to fairly large sized dimensional scatterers¹. One interesting extension of the new method is to solve the problem of multiple scattering involving dielectric and metal targets.

In the multi-body scattering the objective of this program is to solve the scattering of two bodies of revolution. The geometries and material of the two scatterers could be different and the distance between them arbitrary. The illuminating plane wave could be arbitrarily oriented and polarized. The bistatic scatterings of the two body scattering will be our computational objective. In the multi-media scattering the target will be a metal wire partially buried in a lossy ground.

Because of the difficulties involved in theoretical verification of the ground computation, an experimental study of the multiple scattering will be an integral part of the program.

State of the Art

Scattering by two spheres was first investigated by Trinks³ in 1935, and then by Germogenova⁴ in 1963, for small spheres. Scattering by two arbitrarily shaped bodies was treated by Zitron and Karp⁵ and was limited to objects separated far apart. The latest attempt to solve the two sphere scattering problem rigorously was by Liang and Lo⁶. While the multiple scattering mechanism was presented by Zitron and Karp⁵ for arbitrarily shaped obstacles, they can only obtain results for scalar fields. In our proposed program, the limitation on the objects is that they be axially symmetric, in addition to the unavoidable limitation of size (diameter less than 2 wavelengths).

The problem associated with scatterers near lossy half space is a problem of evaluation of Sommerfeld's integrals. Because the integral has to be evaluated many times in solving the integral equation, the economics of evaluating Sommerfeld's integral is essential to the problem. So far, the investigation of Sommerfeld's integral has been studied extensively for the case where the scatterer is entirely above the ground. Little has been done to evaluate Sommerfeld's integral where source and field points are in different regions. The only effort was

that presented by Kuo and Mei* Further study of Sommerfeld's integral in cross regions is needed for this project.

Progress and Publications Since Last Major Proposal

1. Experimental System

Considerable experimental results have been obtained on high-frequency scattering by multiple spheres⁷. These were primarily back scatter measurements because bistatic measurements involved considerable difficulties; consequently, a refinement of the equipment was undertaken.

A semi-automated radar cross-section measurement system has been developed where it is possible to obtain scattering data to be used as verification of the numerical results. The system consists of an indoor image ground plane with a CW microwave system operating in the x-band. It utilizes the well-known null balance technique for extracting the scattered field. A process computer is linked to the system via a network analyzer which is used as a coherent detector. The measurement system employs a reciprocal measurement technique (RMT) which enables one to obtain bistatic scattering data². The process computer stores and removes inherent errors in the system and processes the data in a variety of formats.

The measurement system has proven successful in verifying previous numerical analysis endeavors¹. The accuracy of the system has been shown to be reliable for cross-sections on the order of the wavelength squared.

2. Computation

The program of scattering by a two metal body of revolution has been completed^{8,9}.

A. Publications under JSEP

J. F. Hunka, "Electromagnetic scattering by two bodies of revolution," Ph.D. Dissertation, University of California, Berkeley, 1979.

K. K. Mei, J. F. Hunka and S.K. Chang, "Recent developments of the uni-moment method," International Symposium on Recent Developments in Classical Scattering, Columbus, Ohio, June 1979. To be published as a chapter in Recent Developments in Classical Scattering, edited by V. K. Varadan, Academic Press.

*Kuo, W. C. and K. K. Mei, "Numerical approximation of the Sommerfeld integral for fast convergence," Radio Science, vol. 13, no. 3, May 1978, pp. 407-415.

J. F. Hunka, "Scattering of twobodies of revolution," to be published in Journal of Electromagnetics, July-September 1981.

K. K. Mei, "Recent developments in the Unimoment Method," URSI 20th General Assembly, Abstracts Sessions of Commissions, p. 390, Washington, D.C, Aug. 1981.

J. F. Hunka and K.K. Mei, "Scattering by two bodies of revolution," IEEE Antennas and Propagation Symposium and USNC/URSI 1980 Meeting, Quebec City, Canada, June 1980.

B. Publications under Other Sponsorship

H. Kao and K. K. Mei, "Scattering by advanced composite bodies of revolution", USNC/URSI Conference, Seattle, Washington, June 1979.

S. Coen and K.K. Mei, "Inverse scattering of layered media," USNC/URSI Conference, Seattle, Washington, June 1979.

S. K. Chang and K. K. Mei, "Generalized Sommerfeld integrals and field expansions in two-medium half-spaces," IEEE Trans. on Antennas and Propagation, vol. AP-28, no. 4, pp. 504-512, July 1980.

Government Scientist Contact

Professor Mei is in frequent contact with scientists of the Army who are interested in the work of electromagnetic scattering.

Significant Accomplishments

We have positively demonstrated that the Unimoment Method is a powerful computational technique to solve scattering problems involving inhomogeneous material targets, [1], and that an iterative technique following the Unimoment Method is an economical approach to solve two-body scattering problems [8]. In an effort to solve two-body scatterings near an air-ground interface, we have investigated a new addition theorem involving Sommerfeld integrals. This investigation has been successful, using the theory of analytic continuation. We are now in a position to implement the new addition theorem to find scattering by two bodies, where one may be above and the other under the ground.

Proposed Research Program

The proposed scheme to solve a multiple scattering problem is to solve the two scattering problems separately first, and then to use the addition theorem to transform the scattered fields of one obstacle to another representation with the origin at the center of the other obstacle. This transformation should enable the Unimoment Method to be applied to a single scatterer using the scattered fields of the companion scatterer as part of the incident fields. The process is repeated alternately on each scatterer and the convergence trend is monitored.

We have no doubt that the process will converge because that is essentially what happened in reality, and because the scattering problem represents an open system which has no lossless resonance phenomenon. The advantage of this iterative approach is that the memory requirement on the computer is not much greater than that for a single scatterer problem. Also, most of the time-consuming computations, such as matrices and their inversions, have to be done only once.

Our research has already shown that the two metal body scattering can be computed accurately and economically. Our new objective is to extend the study to multi-body scattering involving multi-material targets, such as dielectric and metal or any other combinations. We shall also study scattering and radiation properties of wire structures which are partially buried in a lossy ground, or the multi-medium scattering, and two-body scattering where one body is above and other under the ground. Recently we have also included the work of time domain approach to electromagnetic scattering. We have formulated a numerical algorithm, so that the time domain finite difference technique may be conforming to the curved boundaries of the scatterer. We intend to begin computation in that direction.

Interaction with Other Work Units

The techniques developed in this research will be applied to other work units in the proposal, such as EM-82-2.

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- (9) K. K. Mei, J. F. Hunka and S. K. Chang, "Recent developments of the unimoment method" International Symposium on Recent Developments in Classical Scattering, Columbus, Ohio, June 1979. To be published as a chapter in Recent Developments in Classsical Scattering, edited by V. K. Varadan, Academic Press.

University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: EM-82-2

Last Year's No.(s): EM-81-2

Title: Millimeter Wavelength Electromagnetic Structures

Senior Principal Investigator(s): S. E. Schwarz
K. K. Mei
D. J. Angelakos

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Scientific Objective

This project is based on the emergence of a new level of millimeter-wave technology, based on use of semiconductor integrated circuits. The electromagnetic structure to be used in this region of the spectrum will probably have to be quite different from those used in existing microwave technology. Appropriate structures (a) should contain little or no metal, as the latter introduces resistive losses; (b) should have dimensions in the range feasible for existing microfabrication technology (loosely speaking, .0002 - 1.0 cm). (c) should yield desired structures without undue fabrication complexity; and (d) should lend themselves to low-cost replication and integration into systems. The scientific objective of this project is thus the realization and analysis of novel antenna and waveguide structures for use in this emerging application.

State of the Art

Conventional millimeter-wave technology at present makes use of hollow metal waveguides. The resulting structures work well in most cases but suffer from problems of cost, size, and fragility; moreover, they become progressively smaller and more difficult to construct as wavelength decreases into the near-millimeter region. The most promising alternative appears to be the slab-coupled dielectric waveguide¹. No exact theory of these guides exists. There is an approximate theory², or, alternatively, numerical methods exist³ that can, at some cost in time and effort, be used in specific cases. Until now these guides have not been adapted for millimeter-wave use, but similar guides have been considered for use in integrated optics^{4,5}. In our own earlier work⁶ we demonstrated the use of these guides in millimeter-wave IC applications by using them as the basis for tapered dielectric antennas. Other possible guiding structures have been proposed⁷⁻¹², but these seem less advantageous due to fabrication difficulty and/or metallic loss. Open structures are also possible¹³ but these are large and lack rigidity. A non-integrated millimeter-wave dielectric antenna was devised by Shiau¹⁴ using empirical formulas due to Mallach and Kiely¹⁵.

Progress and Publications

Publications Under JSEP and Other Support

C. Yao, S. E. Schwarz and B. J. Blumenstock, "Monolithic integration of a dielectric millimeter-wave antenna and mixer diode: an embryonic millimeter-wave IC," submitted to IEEE Trans. on Microwave Theory and Techniques.

Significant Accomplishments

D. B. Rutledge completed his Ph.D. with JSEP support in June, 1980. He is presently an Assistant Professor at California Institute of Technology. From his work and collaborations there resulted a new type of

detector array and a novel microbolometer for infrared detection. This detector consists of a thin bismuth bolometer film with dimensions much smaller than a wavelength. The small size of the detector results in reduced NEP and faster response. A video NEP of 1.6×10^{-10} W/Hz^{1/2} is obtained at 119 μ m, remaining within a factor of 10 of this value for modulation frequencies up to 25 MHz. When used as a mixer, the device is predicted to have an NEP of 3.5×10^{-18} W/Hz. It is easily fabricated with conventional planar processing techniques and can be replicated in arrays. The device is expected to be most useful when the radiation to be detected is spatially coherent.

Proposed Research

The most promising basic component for millimeter-wave IC's appears to be the dielectric "slab-coupled" or "ridge" waveguide. Although this type of guide was proposed and studied earlier^{1,2}, it appears not to have found applications until now, and thus has not been extensively analyzed. Existing theory is highly approximate, due to the fact that the guide boundaries do not fall on coordinate surfaces. Precise theoretical analysis is possible but requires laborious computation. Our intention is to make use of both approximate and computational techniques, but to supplement them with simulation experiments at X-band. By this means it will be possible to obtain dispersion curves for variously shaped guides of this family and compare them with theory. Electromagnetic field distributions will also be studied.

When the guides are adequately characterized, we shall go on to study their potential use as a basis for other components. For example, it seems logical to create a hybrid coupler by bringing two of these guides close together, so they couple through the fringing fields of their common slab. However, this raises significant electromagnetic questions. We must determine whether the guides can be curved (in order to bring them together and separate them) without excessive radiation loss. Radiation losses will depend on the dimensions of the guide and this dependence must be studied. The design of such a coupler will also require detailed knowledge of the fringing fields. Thus before such a coupler can be effectively designed, theoretical and experimental studies of the guided fields must be made.

An interesting alternative to the use of curved guides is the possible introduction of abrupt double bends, such as are used in hollow metal waveguides. The basic idea here is to obtain the desired deflection by using a sequence of two bends, the reflection of the second of which is used to cancel the reflection of the first. "Fine-tuning" of such a structure can be applied by perturbing the shape of the guide. This approach will be studied as a way of obtaining more compact bands with possibly reduced radiation loss.

An especially interesting application of the dielectric guides is their use in resonators. There is a serious need for new radiation sources in this region of the spectrum, especially integrable ones, and these new sources will need integrable resonators. Evident ways of

producing resonators based on slab-coupled guides includes (a) circular "racetrack" resonators with hybrid couplers; (b) "open-circuited" sections of guide with perpendicular cleaved end-faces; or (c) guides with periodic distributed-feedback structures. All of these, when looked at more closely, are relatively sophisticated structures, for which careful analysis will be required. Related problems we also propose to study are (a) how can such resonators be tuned? and (b) how can active elements be coupled to them to create oscillators? In regard to (a), we plan to study perturbation of phase velocity caused by presence of adjustable external dielectrics in the fringing fields. With regard to (b), two possibilities are being investigated. One is the use of metallic couplers such as have been used with mixer diodes in earlier work; the other is incorporation of large-area devices directly in reduced-height guides, with electromagnetic coupling. It is hoped that enough understanding of the requisite structures can be gained to make new mm-wave sources a practical possibility.

During the last year we have proceeded with our program of characterization of the "rib" waveguide. By means of probe measurements dispersion characteristics have been determined. More recently we have worked on optimal design of the V-coupler used to couple diodes to the guide. We plan to continue this work and to develop design rules for this unusual and useful component. In particular, our objective is to reduce the coupling loss between diode and guide, by optimal choice of the coupler and guide dimensions.

When design of the V-coupler has been completed we shall proceed to the previously-described design studies of hybrid couplers and resonators. The resonator studies, especially, are urgently needed for development of monolithically-integrated radiation sources. Development of the semiconductor devices is being carried on concurrently under other support.

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

II.A. Basic Research in Solid State
Electronics - Materials

Coordinator: Professor S. Wang

General

Two important aspects of material research concerning microstructure engineering are control of growth and doping process, and understanding of interface problems. In the Electronics Research Laboratory, we have developed extensive expertise in silicon technology and, to a lesser degree, in GaAs technology. Processing steps such as lithography, impurity diffusion, plasma etching, ion beam milling, ion implantation, and liquid-phase-epitaxy (LPE) have been widely and routinely used. Recent advances in thin-film growth technology, especially chemical vapor-phase deposition (CVD) and molecular beam epitaxy (MBE), have opened new options in the fabrication of submicron electronic devices. Through JSEP funding, we recently purchased a Riber MBE system and are in the process of ordering a scanning Auger microprobe (SAM). These facilities greatly enhance our experimental capabilities in thin-film growth and in interface studies. A great deal of our research effort will be focused on developing the capabilities of the MBE system and the SAM instrument, and applying these capabilities to thin-film growth and analysis.

It is conceivable that fabrication of future submicron electronic devices will involve a combination of several growth and processing steps, such as MBE, ion implantation, laser annealing, and heat treatment. It is our plan to develop the capability not only in growing thin films under controlled conditions, but also in determining the impurity distribution and composition profile in the grown films before and after the various processing steps. Processing and growth steps, such as ion implantation and MBE, either introduce lattice defects or involve high doping concentration beyond the solid-solubility limit, or both. These problems must be investigated. Since the MBE technology has been most developed for GaAs/(GaAl)As and since we already have extensive experience with LPE growth of GaAs/(GaAl)As films, our initial effort on the MBE system will deal mainly with GaAs/(GaAl)As materials. A research program on the MBE process is presented under SSM-3 entitled "Molecular Beam Epitaxy and its Application to Studies of Material Aspects of Microstructure Engineering."

As the dimension of electronic devices is reduced further and further, the interfaces of a device are expected to play a more and more important role in affecting the device performance. Even for silicon devices which have been most extensively studied, many important interface problems remain to be understood and overcome. One such problem relates to hot-electron injection and trapping at the interface between silicon and overlying insulator layers. A major effort will be focused on the development of an understanding of interface traps in both their properties and in their effects for modeling. A research program on determining trap density and cross section and on modeling channel hot-electron emission is presented under SSM-1 entitled "Hot-Electron Injection and and Trapping at Si/Insulator Interfaces." In parallel with this effort, a research program on metal-compound

semiconductor contact is discussed under SSM-3.

Besides Si and GaAs, a great deal of attention has been paid recently to the quaternary compound (GaIn)(AsP) and the ternary compound $\text{Ga}_{0.47}\text{In}_{0.53}\text{P}$, the former for its spectral coverage as a laser for fiber optical communication, and the latter for its high electron mobility and peak drift velocity. Compound semiconductors have many distinct advantages over silicon. Compounds of larger gap energy can be made semi-insulating by compensation and compounds of smaller gap energy have very high electron mobility. The miscibility and the possibility of lattice-match of these compounds enables us to build electronic and optical devices with materials different from the substrate and thus to take full advantage of the material properties. A research program on the LPE growth of the quaternary compounds, the quaternary-compound laser, and the metal-quaternary compound contact is presented under SSM-2 entitled "III-V Compound Semiconductors: Material Properties and Device Studies."

In summary, three research programs are proposed in MBE technology, in interface studies and in the quaternary compound (GaIn)(AsP). The main objectives are: (1) to study the characteristics of the MBE process and to explore potential use of the MBE process for fabricating submicron electronic devices; (2) to determine the electrical and material properties of a metal-semiconductor interface and to study the effects of interface properties on the device performance; and (3) to develop the processing technology for the quaternary compound and to explore the possible use of the compound for integration of electronic and optical devices.

University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: SSM-82-1

Last Year's No.(s): SSM-81-1

Title: Hot-Electron Injection and Trapping at Si/Insulator Interfaces

Senior Principal Investigator(s): C. Hu

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Scientific Objective

The objective of this work is to characterize and understand hot-electron injection and trapping at the interface between silicon and overlying insulator layers, and to investigate means of gaining control over these phenomena. A major effort will focus on the development of an understanding of interface traps and of the influence of hot electrons on the valence and densities of these traps.

State of the Art

Hot electrons can be injected into silicon dioxide in several ways. An important example is channel hot-electron injection¹, which occurs with increasing likelihood as MOSFET channels are shortened and which imposes practical constraints on the operating voltage of short channel MOSFET's^{2,3}. Injection can also take place through internal photoemission⁴, Fowler Nordheim tunneling at high fields⁵, and avalanche breakdown near the Si surface⁶. Once a conduction electron enters the oxide, it can be captured by traps in the SiO₂ band gap formed by impurities or defects. The buildup of trapped charge Q is often monitored by measuring the change of the flat band voltage ΔV_{FB} - usually through C-V measurements. If the approximate location of the traps is known, then we can determine Q from $Q = \frac{d_t}{d_t} V_{FB}$, where d_t is the centroid of the trapped charge measured from the metal-SiO₂ interface. It is clear that the technique senses the internal field at the Si/SiO₂ interface created by charge Q. This method, however, cannot be reliably applied to studying SiO₂ grown from poly-crystalline Si. One other technique can sense the field at the interface - the photocurrent-voltage⁷ technique. This method, however, is inconvenient to use. We propose to measure the change in the internal field due to Q by measuring the shift of the I-V curve. In other words, the Fowler-Nordheim injection is used both as the mechanism of electron injection, and as a means of measuring Q.

Using a first-order, rate-process model, it can be shown⁸ (given a trap density N and capture cross section σ) that:

$$Q = q N (1 - e^{-\sigma F}) \quad (1)$$

$$F = \int_0^t \frac{J(t)}{q} dt \quad (2)$$

where J is the current density and F is the electron fluence. Hence, an established procedure is to measure Q as a function of F and then to extract N_t and σ from the data by curve fitting with Eqs. 1 and 2. As a result, only discrete values of σ have been reported for traps in SiO₂ grown from single crystal Si without regard to possible spreads of σ over a finite range.

Finally, a quantitative model of channel hot-electron injection is presently not available. It has only been established that as electrons move from source to drain, they become sufficiently heated so that some

attain the energy needed to surmount the 3.2 eV barrier at the Si/SiO₂ interface and enter the oxide.

Progress and Publications

Without JSEP support, we have already studied Fowler-Nordheim tunneling into SiO₂ grown from poly-Si and observed electron trapping⁹ (C. Hu, Y. Shum, T. Klein, E. Lucerno, Appl. Phys. Lett., July 15, 1979). We have developed a method for determining the trap cross-section and density distribution¹⁰ (C. Hu, D. Y. Joh, Y. Shum, T. Klein, IEDM, Dec. 1978, pp. 229-232), together with a ballistic model of hot channel electron transport and emission into SiO₂¹¹ (C. Hu, IEDM, Dec. 1979, pp. 22-25). We have carried out extensive studies on gate currents in avalanche gated diodes¹² (R. Amantea and R. S. Muller, Jap. Jour. Appl. Phys., vol. 16, Suppl. 16-1, pp. 205-210, 1977), and have built special resistive-gated MOSFET's to assure uniformity of injection along the channel¹³ (P. K. Ko and R. S. Muller, IEDM, 1979, pp. 506-507).

Since the start of this project in June, work has begun in sample preparation and assemblage of a measurement system. The samples are silicon-gate MOS of varying channel lengths and other device parameters. An HP 9845A desktop computer and HP 9885M disk cartridge are employed to control the current source and the programmable DMM as well as to store and process the data.

Under terminating JSEP support, the following publications appeared in the interim: "Arsenic-implanted Si layers annealed using a cw Xe arc lamp," C. Drowley and C. Hu, Appl. Phys. Lett. 38, P. 876-878, June 1981; "Velocity of surface carriers in inversion layers on silicon," R. W. Coen and R. S. Muller, Solid State Electronics, 23, pp. 35-40, 1980; "Dual-gate depletion-mode DMOS transistor for linear gain-control application," S. Kwan, C. T. Chung, R. S. Muller and R. M. White, IEEE Trans. on Electron Dev., ED-26, pp. 1053-1057, July 1979.

Proposed Program

Two topical areas will be investigated simultaneously: (A.) trap density and cross-section distributions in gate insulators, and (B.) models for hot electron emission from MOSFET channels.

A. Trap Density and Cross-section Distributions

The two parameters linked most closely to electron trapping and device stability are trap density and capture cross-section. Below, we describe a method that determines the trap density per unit cross-section as a continuous function of the capture cross-section $N(\sigma)$ - - a task hitherto untenable.

From first-order rate processes, the density of filled traps $N_f(\sigma)$ increases according to

$$\frac{dN(\sigma)}{dF} = \sigma[N(\sigma) - N_f(\sigma)] \quad (3)$$

The solution of (3) is

$$N_f(\sigma, F) = N(\sigma)(1 - e^{-\sigma F}) \quad (4)$$

The shift in the C-V or I-V curves, ΔV is related to the filled trap density by

$$\Delta V = \frac{d_t Q}{\epsilon} = \frac{q d_t}{\epsilon} \int_0^\infty N_f(\sigma, F) d\sigma \quad (5)$$

$$\begin{aligned} \frac{d\Delta V}{dF} &= \frac{q d_t}{\epsilon} = \int_0^\infty \frac{dN_f(\sigma, F)}{dF} d\sigma \\ &= \frac{q d_t}{\epsilon} \int_0^\infty \sigma N(\sigma) e^{-\sigma F} d\sigma \end{aligned} \quad (6)$$

Clearly, $\frac{d\Delta V}{dF}$ is the Laplace transform of $\frac{q}{\epsilon} d_t \sigma N(\sigma)$. The distribution $N(\sigma)$ can be obtained by taking the inverse Laplace transform of the measured $\frac{d\Delta V}{dF}$. If $\frac{d\Delta V}{dF}$ can be approximated by an analytic function, the inverse transformation is often easy to carry out. Otherwise, numerical techniques can be employed.

We propose to use this method to investigate the dependence of trap densities and cross-section distributions on the growth conditions for the insulator, the exposure to radiation, of the MIS system, and the annealing conditions used in the fabrication process. Even the more conventional characterization techniques have not been applied to the most promising insulators in submicron devices. We propose to study the traps in very thin ($< 300 \text{ \AA}$) SiO_2 , thermal as well as CVD nitride, SiO_2 grown on poly-Si -- both as-deposited and laser-annealed.

B. Modeling Channel Hot-Electron Emission

Channel hot-electron emission is expected to be a principal problem affecting the reliability of short channel MOS devices for VLSI.

Modeling of this phenomenon has been hindered by the large number of variables involved and the inability to verify the individual building blocks of the model¹²⁻¹⁴. We propose to develop a relatively simple ballistic transport model, whose central premise is the verified and accepted "lucky electron model"² originally introduced for hot-electron emission into the substrate. The modifications needed for channel hot-electron emission are to require that an electron gains sufficient energy from the field, and that it be redirected by acoustic phonon

scattering toward the Si/insulator interface before suffering an energy-robbing, intervalley-phonon scattering. Also included are the scattering in the finite distance between the channel electrons and the interface and in the image-force potential well in the oxide. The only device-dependent input to the model is potential distribution in the channel along its length, which may be obtained from approximate analytic formulas or from computer models of the device.

This model should be able to predict the dependence of the channel hot-electron emission rate on V_g , V_{ds} , channel length, gate-oxide thickness, and the channel doping profile. We have developed a preliminary version of such a model¹¹, but much more needs to be done. The final model would likely make use of the multi-dimensional device simulation programs being developed elsewhere to calculate the surface potential distribution between the source and drain.

Even the preliminary model has suggested several intriguing concepts that we propose to study experimentally in parallel with refinement of the model. The ballistic "lucky electron" model suggests that if the drain-source potential is kept below 2.5 volts, the channel hot-electron emission is very small -- regardless of how short the channel may be. If this is borne out by experiments, it could have far-reaching impact on the physical limitations of very short channel FET's.

Another concept suggested by the model is that the hot-electron emission is almost uniquely determined by the maximum field strength in the channel. If so, it should have a one-to-one correlation with the substrate current, which has been theoretically correlated to the maximum field, E_m :

$$I_{sub} = I_d A e^{\beta E_m}$$

where A and β are material constants.

The correlation between channel hot-electron emission and I_{sub} would allow us to do device characterization and accelerated reliability tests of the hot-electron instability by simply measuring I_{sub} . This procedure would supplement or possibly replace the long-term stress tests, which are the only available means of assessing the device instability associated with hot-electron phenomena.

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Work Unit No.: SSM-82-2

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Title: III-V Compound Semiconductors: Material-
Property and Device Studies

Senior Principal Investigator(s): S. Wang
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Scientific Objective

We propose to study the properties of the quaternary compound (GaIn)(AsP) and the ternary compound $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ concerning LPE growth, lasing characteristics, ohmic-contact formation, and Schottky-barrier height. The quaternary compound is important for its spectral coverage best suited for fiber optical communications, and will be studied as laser material. The ternary compound is promising for its theoretically predicted high mobility and peak drift velocity. Our objectives are to find the dominant factors affecting LPE growth, lattice mismatch, impurity concentration, contact resistance and Schottky-barrier height in these materials, and to correlate the material properties, such as lattice mismatch, doping profile and material-composition profile, with the device performance, such as lasing characteristics, turn-on voltage, and I-V characteristics, and with the electrical measurements, such as carrier concentration and mobility.

State of the Art

III-V compound semiconductors possess many distinct and unique advantages as an electronic and optical material. Most of the compounds of smaller gap energy, such as InAs and InSb, have very small electron mass and thus exceedingly high electron mobility. Some of the compounds of larger gap energy, such as InP and GaAs, can be made semi-insulating by compensation either through deep donors or through deep acceptors. The compounds are almost completely miscible except in some systems where a small miscibility gap exists. The mixed compounds can be lattice-matched to a given substrate, for example $(\text{Ga}_{1-x}\text{In}_x)(\text{As}_{1-y}\text{P}_y)$ to InP, by properly choosing the relative composition signified by x and y. The miscibility and the possibility of lattice-match of these compounds enable us to build electronic and optical devices with materials different from the substrate and thus to take full advantage of the material properties, for example (GaIn)As on InP, with the former for its high mobility and the latter for its semi-insulating property.

Most of the compounds are direct-gap semiconductors and hence attractive candidates as materials for lasers and photodetectors. In compounds where the energy gap is direct, the energy separation between the central valley (the direct gap) and the satellite valleys (above the central valley) of the conduction band varies from compound to compound. This variation offers various possibilities for mixed compounds. For mixed compounds with relatively small separation, for example 0.36 eV in GaAs, we expect the material to exhibit the so-called transferred-electron or Gunn effect. For mixed compounds with relatively large separation, we expect that the material should be able to attain a much higher drift velocity than the value limited by the transferred-electron effect. The possibility of a high drift velocity makes these materials attractive candidates for FET. In any case, on a time scale shorter than the intervalley-scattering time, the electron drift-velocity is expected to continue to grow with increasing applied field to values beyond those limited by the transferred-electron effect. This

phenomenon, called velocity overshoot, makes compound semiconductors extremely attractive for ultra-high frequency applications.

Among III-V compounds, the GaAs/(GaAl)As system has been most extensively studied for both laser¹ and FET² applications. For the laser, a great deal of attention has been focused on stabilizing the mode by incorporating a two-dimensional waveguide in the structure, and remarkable progress has been made on the GaAs/(GaAl)As laser. Many lasers exhibiting linear light-versus-current relation, stable transverse and lateral mode pattern, and single longitudinal mode operation have been developed at several laboratories. These include the buried-heterostructure (BH) laser^{3,4}, the channeled-substrate-planar (CSP) laser^{5,6}, and the laser utilizing thickness variation in the grown layer to provide waveguiding in the lateral direction⁷⁻¹⁰. Among the lasers referenced here are the IRW laser⁷, the CJSF laser⁷ and the narrow DCC-CSP laser⁶ being developed and studied in our laboratory. Recently, the research interest has shifted from the GaAs/(GaAl)As laser toward the quaternary (GaIn)(AsP)/InP laser which covers the spectral range where optical fibers have exhibited minimum loss (around 1.55 micrometers) or zero dispersion (around 1.3 micrometers). Because the development of the quaternary laser is relatively recent, many problems including mode stability and temperature sensitivity have not been fully investigated and are yet to be overcome.

For the field-effect transistor, the emphasis is on low power and high speed, and a power/speed product around 20 fJ and a propagation delay around 100 ps have been reported by several laboratories (see papers appearing in the special issue of MTT, Reference 2). To further advance the FET technology, several important problems need to be overcome and have received prominent attention. One of the steps used in the fabrication of the FET is ion implantation. It is found, however, that considerable degradation of the doping profile takes place during annealing of Cr and S implants¹¹⁻¹³. Although anodic oxidation has been tried on compound semiconductors¹⁴, the interface-state density is considerably higher than that at Si/SiO₂ interface. For lack of a suitable insulator, most FET's are made of Schottky-barrier gates in the form of MESFET. However, the barrier height formed on Si and GaAs is generally not as high as we hope to have. Theoretical studies^{15,16} have shown that the degree to which the barrier height at a metal-semiconductor interface is influenced by the metal work function is strongly dependent on the ionicity of the semiconductor. Because Si and GaAs are covalent the barrier height in these two materials is not expected to change much with the metal, as confirmed by experimental data¹⁵. Therefore, an interface material, such as silicide for silicon, must be found for compound semiconductors between the metal and the semiconductor.

Recently, the ternary compound In_{0.53}Ga_{0.47}As has generated considerable interest, not only as a photodetector for the quaternary (GaIn)(AsP) laser, but also as a FET¹⁷. Theoretical calculations¹⁸ of the low-field mobility and the peak drift velocity in the ternary compound show that $\mu = 9700 \text{ cm}^2/\text{v-s}$ and $v_m = 2.8 \times 10^7 \text{ cm/s}$ are higher than the corresponding values in GaAs and InP, even with alloy scattering being taken into account. The quaternary (GaIn)(AsP) and the ternary In_{0.53}Ga_{0.47}As compounds offer exciting research opportunities for their

outstanding properties and for their relatively unexplored status. Our research efforts will be concentrated at first on those aspects for which we have acquired expertise and then extended to areas which, we think, are important and in which we can make significant contributions.

Progress and Publications

In the last progress report, we mentioned that we had started LPE growth of InP films on InP substrates and fabricated a few stripe-geometry lasers. We were able to achieve lasing action in a majority of the lasers tested. With a 10 μm stripe width, a surprisingly small threshold current as low as 180 mA has been obtained. Since then, we have made a great number of stripe-geometry lasers and taken x-ray measurements of the lattice constants of the grown layers. The threshold current depends to a great extent on how well the quaternary (GaIn)(AsP) layer is lattice matched to the InP substrate. The wafer showing the low threshold current actually has a lattice mismatch almost comparable to the resolution of the x-ray measurement and smaller percentage-wise than that of the $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}$ film relative to the GaAs substrate. However, the results on lattice-matching have not been consistent, even with great care in melt preparation. One problem in causing the nonreproducibility of the results is the accuracy required in the weight of GaAs and InP charges relative to the In melt. The GaAs and InP charges have to be etched before being put into the melt. Procedures are now being established to carefully weigh the GaAs and InP charges before and after etching to establish the etching rate. An order has been placed through industrial funds to purchase a microbalance to accurately weigh the GaAs and InP charges.

In the meantime, we have performed experiments on Zn diffusion into InP, and obtained consistently good results. We have developed, in conjunction with Zn diffusion into GaAs, an ampule which minimizes zinc deposition onto the sample during cooling. We believe that the zinc diffusion process is now under control. Also, we have investigated the possibility of making quaternary ring lasers. Experiments on an etched high-mesa ring laser are now in progress. Our tasks are concentrated on (1) finding an etchant which will etch smoothly the side wall of the ring to minimize scattering losses, and (2) finding a suitable self-alignment scheme which will automatically define a path confining the current to the outside periphery of the ring. The results on etching appear reasonably good, but the electrical contacts do not seem to have uniform coverage of Au. Steps are taken to correct the situation.

On the theoretical side, we have studied various configurations for a semiconductor ring laser to derive some advantages over the simple Fabry-Perot laser. We have completed two papers - one paper entitled "Novel Semiconductor Lasers for Integrated Optics" will be presented at the SPIE symposium to be held at Huntsville, Alabama on Nov. 16-19, 1981, and one paper entitled "Studies of Semiconductor Lasers of the Interferometric and Ring Types" has been submitted to IEEE J. Quantum Electron., for possible publication in the special issue on Guided-Wave Optics Technology. In brief, we have found a suitable configuration for the ring laser which consists of a circular guide and two straight guides. Even though any reflection in a non-ideal ring laser will

couple the two counter-running waves, one fundamental difference between a non-ideal ring laser and a Fabry-Perot laser remains, that is the existence of internal feedback in the former to couple a laser mode back to itself. The existence of this internal feedback opens up new possibilities which do not exist for the Fabry-Perot laser. Interesting possibilities include (1) the excitation of one predominant circulating mode at the expense of the opposite running mode, (2) the reduction of the effect of optical feedback on the dominant lasing mode, and (3) the elimination of at least one laser mirror for making direct optical integration and use of an optical isolator possible.

Proposed Research

As discussed in the section on state of the art, the quaternary $(\text{Ga}_{1-x}\text{In}_x)(\text{As}_{1-y}\text{Py})$ compound and the ternary $\text{Ga}_{0.53}\text{In}_{0.47}\text{As}$ compound have outstanding properties, as laser material for the former, and as photodetector and FET material for the latter. These materials, compared to the $\text{GaAs}/(\text{GaAl})\text{As}$ systems, are still in the infant stage of investigation, even though rapid progress is being made in material and device studies. In our laboratory, we have acquired expertise in the $\text{GaAs}/(\text{GaAl})\text{As}$ material through our work on the injection laser and have gained experimental skills in measurements of electronic properties of semiconductors through our work on integrated circuits. Recently, through JSEP funding, we purchased a Riber MBE system with separate growth and analytical chamber. Although the growth chamber initially will be devoted to the $(\text{GaAs}/(\text{GaAl})\text{As}$ system, the analytical chamber can and will be used for other semiconductors. Our research activities in the area of the quaternary and ternary compounds will be planned according to the availability of the analytical instruments insofar as the use of the MBE system is concerned. In the following discussion, specific research plans are presented.

As mentioned in the section on Progress, we have already successfully grown LPE layers of quaternary compounds of excellent quality and achieved lasing action at 1.248 micrometers in stripe-geometry lasers. The composition required for lattice match to InP is well documented in the literature and strictly followed in our growth process. The lattice match has been checked by x-ray diffraction, and the LPE grown quaternary layers will be checked periodically for lattice match. The low threshold current observed is a good indication that the amount of lattice mismatch is most probably within tolerance limits. Our current efforts on the quaternary laser relate both to the laser structure and to the material property. On the laser structure, our effort will be concentrated on the ring laser. As discussed in the Progress and Publications section, the ring laser, even though non-ideal, possesses certain very interesting potentials which are not possible with the Fabry-Perot laser.

As regards to the laser structure, we have developed during the past three years several $\text{GaAs}/(\text{GaAl})\text{As}$ lasers (the IRW laser⁷, the CJSF laser⁷, and the narrow DCC-CSP laser⁶) under QE-1, Thin-film and Guided-wave Active Optical Devices. These lasers show linear light current relation, stable fundamental mode in both transverse and lateral directions, and single longitudinal mode over a wide current range. In

contrast, the radiation pattern and the longitudinal mode behavior of the quaternary laser have been reported only over a very limited range of pumping current and show deterioration at high currents. During our laser study, the cause for the laser sensitivity to temperature will be studied as this material property is expected to affect other devices. Although Auger recombination is believed to be the major cause for sensitivity to temperature, other causes such as carrier diffusion across the barrier can not be ruled out. Possible laser structures with built-in barriers will be explored. Also, particular attention will be paid to the special chemical and growth properties of the quaternary compound so that what we learn from laser fabrication can be applied to other device fabrication. Recently, two vertical configurations have been proposed for the GaAs FET, one utilizing an etched V groove¹⁹ and the other utilizing Be ion implantation²⁰. We propose that laser studies also be made on the structure utilizing LPE growth over an etched channel. We choose this structure because we can learn from it both the etching and growth properties pertaining to a V groove. Further, special attention will be paid to lattice match in the groove region, as any mismatch will certainly show in the laser performance.

An integral part of our laser study is formation of ohmic contact. This subject is again basic to other devices. It is well known from the work on silicon that a low-resistance contact is made of either a tunneling junction or a Schottky barrier of small barrier height. The former is preferable but it requires a high doping concentration. The p-side contact is especially troublesome because it needs high doping to become degenerate on account of the large hole mass. The general adopted way of making an "ohmic" contact is to evaporate Au/Zn on the p side and then form the contact by alloying at the eutectic point for a short time (say, at around 430° C for 20 sec for p-InP). Here the control of the temperature and the time is critical. The usual way of having the alloying process taking place in a heater lacks the precise control we need, and the results vary from run to run. We have tried the alloying process using electric pulses and obtained surprisingly good results. These experiments were performed on samples which showed high turn-on voltage after the usual "alloying" process. After applying electric current pulses of certain magnitude and pulse width, a gradual reduction of the turn-on voltage was observed. The current-pulse method of alloying has the distinct advantage that the pulse height, the pulse width, and the time duration can be accurately controlled and the result of the alloying process can be monitored by the I-V characteristic. We propose that our present work be continued so that a systematic way of making uniform, low-resistance contact can be established to minimize heat dissipation in devices made of quaternary compounds.

As the research progresses, we plan to extend our LPE growth to the ternary compound $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ and our work on ohmic contact to n-type, and start work on Schottky barriers for both the quaternary and the ternary compound. Experiments to determine the doping concentration by the C-V measurement and to find the carrier mobility by Hall measurements are standard procedures in the IC laboratory. Now we have the new capability of determining the composition and impurity concentration in highly doped samples by the AES analyzer. Once the ion-etching package becomes available and operational, we will deep-profile the impurity

concentration in the LPE grown layer and across the semiconductor-metal interface to correlate the depth-profile measurement with the electrical measurements. Also, as mentioned earlier in the section on state of the art, in view of the covalent nature of III-V compounds^{15,16}, an interface material is needed in order to significantly change the barrier height of a Schottky diode. Suitable metals such as Pt, which forms a silicide on Si, will be tried on the quaternary compound, and again the depth-profile measurement will be made to determine the interfacial composition and to correlate it with the electrical properties of the metal-semiconductor contact.

Interaction With Other Work Units

Close interaction is expected with the work units on MBE and on ion-implanted semiconductors, and frequent consultation is also anticipated with other work units, mainly in the IC and device area, for electrical measurements.

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

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Work Unit No.: SSM-82-3

Last Year's No.(s): SSM-81-3

Title: Molecular Beam Epitaxy and its Applications to Studies
of Materials Aspects of Microstructure Engineering

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Scientific Objective

Recent advances in thin-film growth technology have opened exciting opportunities, not only in the development of new device structures, but also in our quest for a better understanding of material properties. The objectives of this research program are (1) to master the MBE growth technology for III-V compound semiconductors and for Si, and to develop the associated processing techniques, such as etching and masking, suitable for the MBE process, and (2) to analyze, to characterize, and to correlate the properties of the materials grown under different growth conditions. Our goals are to seek an optimal approach and to develop the needed technology for fabrication of devices of micron and submicron dimensions where interface and surface properties are expected to play a crucial role.

State of the Art

Over the last several years, significant progress has been made in the thin-film technology based on epitaxy for the fabrication of optical and microwave semiconductor devices. The three basic methods are liquid-phase epitaxy¹ (LPE), vapor-phase epitaxy² (VPE), including metal organic chemical vapor deposition² (MO-CVD, a form of VPE), and molecular beam epitaxy³ (MBE). Among the three, LPE is the most extensively used, especially in the fabrication of double-heterostructure (DH) injection lasers. While the LPE technology has some distinct advantages over the VPE and MBE technology, it has its limitations. One obvious disadvantage is the lack of control on the film thickness and the impurity profile due to the fast growth rate. Another serious drawback is the impossibility of monitoring film growth and having the growth process temporarily stopped for analytical examination of the grown film. The MBE technology provides the answer to these problems and seems well suited as a research tool for the fabrication and study of semiconductor devices of micron and submicron dimensions.

One problem for which we must find a solution if we are to improve the quality of epitaxially grown films of compound semiconductors is the incorporation of unwanted impurities during the growth process. For example, a dominant shallow donor⁴ was found in LPE-grown (GaAl)As and this impurity was thought to be sulphur introduced into the melt with aluminum. Contaminants⁵ such as transition metals were reported to be present in MBE-grown GaAs. The total contamination incorporated in a MBE-grown film may be written as

$$C = (\xi/r_g) (d^2N/dt ds) \quad (1)$$

where C is the impurity concentration, ξ is the sticking coefficient, r_g is the growth rate, and $d^2N/dt ds$ is the number of contaminant gas molecules striking the growth surface per cm^2 per sec. From kinetic theory of gases,

$$d^2N/dt ds = 3.5 \times 10^{22} P/(MT)^{1/2} \quad (2)$$

where P is the partial pressure, M is the molecular weight, and T is the background gas temperature. Take CO as an example which has $M = 28$ AMU. At a typical growth rate $r/r_u = 1 \mu\text{m/hr.}$, the product ξP must be smaller than 7×10^{-15} in order to ensure $C < 10^{14} \text{ cm}^{-3}$. This simple calculation tells us that we must be extremely careful with contaminants with high sticking coefficients and high vapor pressure. It is important, therefore, for us to have analytical equipment, such as CMA and SIMS, to perform chemical analysis of the grown film and to use electrical measurements, such as transient capacitance-voltage spectroscopy, to characterize the incorporated impurities.

Both the MBE and the MO-CVD growth techniques are capable of producing high-quality films as demonstrated in multiple quantum-well (MQW) heterostructure lasers.^{6,7} Recent results on photoluminescence indicate, however, that while Al-Ga disorder alloy clustering seemed to have taken place at the MQW heterostructure interfaces in the MO-CVD films,⁸ no evidence of clustering showed in the MBE films.⁹ The experiment is an example of the need of employing a multitude of experiments in characterizing and comparing films grown by different processes and under different conditions. Even though lasers of low threshold current densities have been reported using the LPE, MBE, and MO-CVD growth processes, defect formation and impurity distribution during either epitaxial growth or subsequent processing remain the topics of intensive study.¹⁰ Defect formation and impurity redistribution not only will affect initially but also may gradually degrade the device performance.

Recently, interest in the MBE growth technology has extended to Si. Iyer et al.¹¹ have proposed a model to explain the dopant incorporation characteristics of MBE grown Si. The smearing of doping profile is explained in terms of a time constant required by the dopants to reach a steady-state concentration. Using "flash-off" and "build-up" techniques, extremely abrupt doping profiles for layers as thin as $\approx 200 \text{ \AA}$ have been achieved. This extra control on the dopant concentration may enable us to incorporate heavily doped or highly resistive layers into the MBE grown Si.

Hetero-epitaxial structures of $\text{Si}/\text{CoSi}_2/\text{Si}$ ¹² and Si/Ge ¹³ have also been demonstrated by solid phase epitaxy.² Since the recrystallization takes place during subsequent annealing cycles, solid state reactions have created interfaces¹⁴ and extended regions of misfit dislocations adjacent to the interface.¹⁵ We believe that such interfacial imperfections can be eliminated or minimized by the MBE technique with coevaporation to form the silicide phase and the $\text{Si}_{1-x}\text{Ge}_x$ solid solution. Moreover, MBE growth can be achieved at substrate temperatures substantially lower than the annealing temperatures required for solid phase epitaxial growth.

Progress and Publications

Under JSEP

The Riber Model 400 MBE system has been assembled and tested. An in-house quadrupole mass spectrometer was installed on the growth chamber of the MBE system. Because the port on the system was designed for Riber's mass spectrometer, an adaptor mount to orient and position properly our spectrometer and a shutter for our spectrometer were designed and assembled. The quadrupole mass spectrometer now works well. A new Phi scanning Auger spectrometer was installed on the analytical chamber of the MBE system. The AES was tested and has been used to detect the presence of any unwanted impurities, especially C, on the GaAs sample after surface cleaning. We follow the procedure used at Bell Laboratories of etching the sample in a $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ etch and putting on the etched surface a protective oxide layer.² Before and after heating in the analytic chamber, the sample was scanned by the AES. The C peak was substantially reduced after heating to a magnitude about 10 times smaller than the oxygen peak. A phi differential pumped ion etching package (including the sputtering gun) has been ordered, and should give us the capability of depth profiling.

Several runs of growing GaAs films on GaAs substrates were made. The films showed reasonably good HEED patterns. Our progress has been hampered by the poor service of Riber. First, Riber delayed the delivery of 5 ovens which were ordered over 9 months ago. The 5 ovens were delivered only recently. This delay prevented us from growing (GaAl)As and doped GaAs films. Second, several mechanical and electrical problems were found, and Riber was very slow in response to our service calls. A small leak in the cryoshroud of the ion pump was found. This leak kept the vacuum in the low 10^{-10} range. We should be able to get the vacuum to the low 10^{-11} range. Also, the HEED gun cannot be focused properly. The service man from Riber was not able to fix the problem. Still another problem was with the meter reading of the ion pump. There appeared to be an excess current, probably due to leakages in the high voltage feedback. These problems have been brought to the attention of the Riber's service and purchasing departments. At the recent MBE workshop many people who have purchased the Riber system expressed similar frustrations with Riber's services.

In the meantime, preparations have been undertaken in setting up photoluminescence (PL) and deep-level transient spectroscopy (DLTS) experiments for material characterization. Both Si samples implanted with proton and GaAs films grown by MBE were used in obtaining the doping profile and the trap energy for the DLTS measurement. A computer program has been worked out for calculating the doping profile from the measured C-V plot. Reasonable results have been obtained for both the doping profile and the trap energy. Both the experiments were set up on borrowed equipment. Now we have gained sufficient experience in both experiments, we are planning on modifying the schematics and on setting up permanent apparatus for the two measurements. The list of equipment requested will be used for the DLTS experiment.

Work on MBE on Si has also begun. So far we have completed the assembly of an ultrahigh vacuum deposition chamber which has a base pressure of $\approx 1 \times 10^{-10}$ Torr. The deposition chamber will be separated from the evaporation chamber with a gate valve. During evaporation, the

evaporant fluxes will enter the deposition chamber via an orifice with the gate valve opened. Decoupling of the two chambers will ensure better substrate cleanliness prior to deposition. In addition, vacuum in the deposition chamber can be maintained at much lower pressures during the evaporation cycle since both chambers are differentially pumped.

A Hall-effect measurement system is also near completion. The set-up has anodic stripping capability which will enable us to profile both the carrier concentration and the mobility of the MBE grown layers.

Recent demonstration of the permeable base transistor²⁰ shows the feasibility of hetero-epitaxial growth of device-quality semiconductor films on metal. This hetero-epitaxy should lead to possible other novel high speed devices such as the metal base transistor.²¹ Such possibilities will be explored for both GaAs and Si.

Proposed Research Program

The availability of an MBE system should greatly enhance our experimental capabilities in the area of microstructure engineering. We have planned the MBE system not merely as a facility for growing thin films, but also as a research tool for studying materials problems important to electronic and optical devices of micron and submicron dimensions. In the MBE system we have the growth chamber is separate from the analysis chamber. This separate arrangement makes the MBE system useful for both film growth and film analysis. We propose the following two main subjects for research: (1) to study and to develop the MBE growth process as a microfabrication technology, and (2) to investigate and to correlate the properties, including interface and surface properties of the film grown under different growth conditions.

The controllability of the thickness, the composition and the doping concentrations of the films grown by the MBE process has been demonstrated in a number of experiments, including super-lattices and DH injection lasers. However, there are other important aspects of the MBE growth process which have not been extensively investigated. We plan to study the effects of growth conditions on the incorporation of electrically and optically active impurities. Both the substrate temperature and the vapor pressures of Ga, As and Al are important growth parameters. Although the MBE films are generally grown under Ga-rich conditions because of the low sticking coefficient of As, it is possible to obtain HEED pattern under the condition of either Ga- or As-stabilized surface reconstruction. The substrate temperature affects the grown film through its effect on (1) mobility of deposited surface atoms, (2) escaping probability of deposited atoms, and (3) diffusion of impurities incorporated into the film. By varying the temperature and pressure we hope to be able to find an optimal growth condition for (GaAl)As system.

The work on the MBE growth process will be divided into two phases. In the initial phase, our work will be concentrated on injection lasers. Although the doping concentrations used are relatively high, we can use measurements of laser characteristics, such as threshold current density and differential quantum efficiency as indications of how well we are able to control the growth process. As we learn more about the MBE

process, we will be better equipped to deal with impurities or defects of much lower concentrations. In the second phase, our effort will be shifted to unwanted impurities. Such impurities would contribute to the background doping concentrations in GaAs and thus limit the operation of such devices as FET's. Such impurities would also contribute to nonradiative recombination in lasers, and thus affect the internal quantum efficiency and possibly the operating life of the laser.

Besides temperature and pressure, another important variable in the growth condition is the substrate itself. One distinct advantage of GaAs over Si is the availability of semi-insulating GaAs substrates upon which electronic and optical devices can be built. It is well known that GaAs can be made semi-insulating by compensation either through deep donors known to be oxygen-related centers or through deep acceptors known to be Cr-related centers. Since many GaAs devices such as FET's and lasers require processing of the wafer at high temperatures such as MBE growth of multilayer structures, the effect of diffusion of impurities in and out of the wafer, as well as in and out of the grown film, becomes an important problem as it definitely will affect the property of the grown film. Thermal conversion of the conduction type (n into p or p into n), probably due to redistribution of the deep-level impurities¹⁶⁻¹⁸, has been reported in the literature, and in our laboratory we have observed a similar effect in O-implanted and Cr-doped GaAs. We plan to use the analytical instruments of the MBE system to provide information on the diffusion of impurities in the films grown by the MBE process on semi-insulating GaAs.

To fully utilize the analytical capability of the MBE system, we plan to study the interface and surface properties, as well as the "bulk" properties of the MBE and LPE films grown in our laboratory. One fundamental element in the family of semiconductor devices is the Schottky barrier diode, basically a metal-semiconductor contact. Although several theories, including the diffusion theory of Schottky and the thermionic emission theory of Bethe, have been shown to give the correct voltage dependence for the current, none of these theories is able to give the correct value for the current or barrier height (the current is a sensitive function of the barrier height). The nonapplicability of the simple theory, even in the absence of any oxide formation at the interface, may be attributed to solid-state reaction taking place between the metal and the semiconductor. We plan to use the analytical instruments of the MBE system to monitor the surface condition of a semiconductor before metal deposition and to determine the interface structure after metal deposition. Since metals generally have a high sticking coefficient at a semiconductor surface, we will try metal deposition in the growth chamber of the MBE system. We propose that the interface properties of metal-semiconductor contacts prepared under controlled deposition conditions be studied for use either as ohmic contacts or as Schottky barrier diodes. The AES analyzer will enable us to detect possible contaminants¹⁹ on the substrate surface prior to MBE growth as we have already done and to determine the interface composition¹⁹ after MBE growth and subsequent processing of the grown films.

To complement the Riber MBE system which will be used for III-V semiconductor studies, we are currently developing a home-made Si MBE system to

fabricate multilayer epitaxial structures. The combined information obtained from both studies will provide us a more complete picture of the MBE growth process and a better understanding of super-lattice electronic properties. Investigations on the following modulated structures have been planned:

- (1) Homoepitaxy — abrupt dopant profiles for Si.
- (2) Heteroepitaxy — (a) Si/Si_{1-x}Ge_x multilayers
(b) Si/silicide multilayers.

We are currently seeking funding for the ultrahigh vacuum evaporation chamber. A dual source with separate E-gun controls is proposed for the deposition of binary phases. The dopants (e.g., Ga and As) will be generated by Knudsen-type cells. Processing and evaluation of some simple devices such as the metal base transistor²¹ and emitter-coupled logic²² will be performed at microfabrication facilities of the Electronics Research Laboratory.

Interaction with Other Units

Close interaction is expected with the work in microfabrication under SSD-83-1, SSD-83-2, with the work on material characterization under SSM-83-1 and SSM-83-2, and with the work on injection lasers under QE-83-1.

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Joint Services Electronics Program September 30, 1981

II. B. Basic Research in Solid Coordinator: Professor T. Van Duzer
 State Electronics - Devices

General

Since 1960 solid-state device research and integrated circuit research have been carried out in a common facility in the Electronics Research Laboratory. We have long maintained and observed the obvious benefit; everyone enjoys a more complete, flexible experimental capability. Further, as a consequence of sharing experimental facilities, there has been a beneficial contact between research in apparently quite different fields. One result is a significant transfer of technique, accelerating progress in experimental technology for all concerned. More subtle results are the development of larger research goals in common.

An excellent example of the interaction of different research groups is the research in electron-beam lithography initiated by Professor Van Duzer and his students nearly 10 years ago to make very fine geometries in Josephson junction structures. This background stimulated work by Professors Neureuther and Oldham to explore advanced lithographies for integrated circuits.

The fabrication facility continues as the focal point for the collaboration between the device, design and technology research activities in solid-state electronic devices. Recent additions to the laboratory have included a Canon FPA projection printer and a Riber molecular-beam epitaxial system. Early in 1981 we will receive a new electron-beam lithography system for precision multi-level structures and a Plasmatherm parallel plate plasma/reactive ion dry etching system.

The proposals contained herein are all advanced device basic studies which use the common laboratory facilities in the experimental phase. They have in common the state-of-the-art techniques required for successful fabrication. Such processes as molecular beam epitaxy, ion implantation, high-resolution lithography, plasma etching, and ion milling will be used, as well as more standard processes such as diffusion and thin-film deposition. The research proposals also have in common certain intermediate and long-term goals. In general the intermediate goals are the basic study and development of simple devices and device models which will point the way toward the long term-goal of more powerful, cheaper, denser circuits.

The most basic studies in this proposal are the investigations in advanced lithography. Progress in all the device studies depends in large measure on advances in the definition of the structures. The electron-beam studies are aimed at an analytic understanding of the factors controlling the ultimate performance of electron-beam lithography systems. The results of such studies would make possible, for example, the application of the extensive Monte Carlo and experimental energy deposition characterization to a wide class of new structures, including,

e.g., Josephson superconductor devices. The proposed photolithographic studies similarly promise to aid in the advance of the integrated-circuit and transducer state of the art.

The proposal on Josephson device studies is aimed at exploring the factors limiting the performance of these devices in the far-submicron size range. Van Duzer and co-workers have demonstrated that they can perform submicron lithography in a modified scanning electron microscope. They have also constructed a number of novel working Josephson structures. They now propose to combine the technologies and make really small circuit cells to explore the problems in this new domain of device size. A number of fundamental theoretical fabrication problems will be encountered and resolved in the course of these studies; it promises to be a very exciting time in the Josephson effect research.

Another proposal deals with techniques for realizing wide-dynamic-range signal processors with integrated circuits. System design and new circuit topologies will be worked out to optimize the technology choices, with parameter choices at process level. Proper noise characterization is essential to achievement of wide dynamic range and forms an important part of the proposed project.

In the final project in solid-state devices a study will be done on piezoelectric polymer-film materials in order to optimize them for transducer applications. The polymers will be formed by plasma-initiated polymerization which makes possible a wide range of process control. It makes possible the formation of relatively mono-disperse, high-molecular-weight polymers. The plasma method also permits polymerization of monomer films in the presence of an electric field, thereby eliminating constraints to their use in transducers and integrated circuits.

University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: SSD-82-1

Last Year's No.(s): SSD-81-1

Title: Critical Problems in Lithography and Their
Impact on Practical Performance

Senior Principal Investigator(s): A. R. Neureuther
W. G. Oldham

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2-2318

Scientific Objective

The objective of this proposal is to attack the problems limiting photo and electron beam lithography and to predict the limits of practical lithography performance as advances are made in the technology. The two problems selected are characterizing the limits of resist performance and the optimization of alignment signals for VLSI. We are constructing automatic systems for determining both development and exposure model parameters of resist materials. The dependence of resist parameters and lithographic performance on process parameters will be investigated both for new resist technologies, and for modifications in existing technologies. We will also use resist profile quality studies as well as basic resist parameter tests to assess the practical limits of lithographic performance. The optimization of alignment signals for VLSI will be based on a study of the fundamental effects of the scattering of electrons or diffraction of photons by various alignment mark features. Where possible the alignment and focus signals for various wafer marks will be characterized by using simple empirical universal models for the components of the marks. System considerations, such as the signal to noise ratio, will be examined from the point of view of optimizing the wafer mark geometry and signal detector system.

State of the Art

Automatic measurement systems for determining both the exposure and development parameters of positive type photoresist were first established a number of years ago at IBM [1]. The exposure measurement approach, which is based on monitoring the change in transmission during UV exposure, is currently being widely adopted. A system of this type has been developed at U. C. Berkeley with appropriate improvements such as full bleaching exposure [2]. The IBM system for determining the development rate parameters is based on an in situ scanning reflectance measurement. This system is much more complicated than the exposure measurement system but a commercial system which is an option on a "Film Thickness Analyzer" is available for about \$100,000. The data rate of this system limits its use to etch rates less than about 300 Å/s. Alternative approaches to produce a less expensive, more accurate, dedicated system are also being made. At U. C. Berkeley in situ capacitive probes [3] and remaining resist absorption techniques [2] have been investigated. The major problems with these approaches are obtaining experimental control over developer flow rates and geometrical areas, and reducing sources of noise in measured signals. There remains a pressing need for a more versatile and more universally applicable automatic system capable of quantitatively measuring general development parameters.

The interest in resist exposure and development parameter data has increased recently due to the public availability of the user oriented program SAMPLE for simulating the projection printer resist line edge profiles [4]. The exposure parameters at several wavelengths and development rate parameters for a few of the popular resists are

available in the literature [5]. However, the available data is lagging far behind the resists and developers of interest today. This gap is likely to widen further with the greater diversity of processing conditions and imaging tools especially with the increasing interest in deep UV wavelengths. A high data rate system is critically needed in order to extract model parameters for existing and new resist technologies.

Several studies of the limits of lithography have been made. These have generally been done on the basis of exposure dose limitations [6] or image contrast [7,8,9]. Such studies have contributed to the understanding of the general importance of various lithography parameters. However, most of the studies of lithography limits have not included the consideration of development effects and are often of questionable practical value. For example, it is at first sight attractive to create a resist with infinite contrast. However, in the presence of the finite edge slope of typical optical images and vertical standing waves for silicon substrates, a resist with infinite contrast would wash out laterally along standing wave peaks long before punching through to the substrate surface. The availability of combined exposure and development simulation [4] now allows these effects which limit the practical use of photolithography to be accurately explored [10,11]. The capability to model multiple process step line edge profiles [12], will allow the developer and compatible processing effects to be examined even more completely at a composite process level. As advances in both the process modeling tools and the fabrication technologies occur, it will be possible to more clearly define the limits of practical lithographic performance.

To realize the benefits of high resolution lithography, alignment and registration techniques must be developed which are accurate to within a fraction of the smallest replicated feature. Automated alignment using amplitude detection with complementary patterns is capable of 0.1 μm accuracy [13] and the use of phase sensitive grating techniques shows even greater potential [14]. Optical projection printing systems now under development are using alignment schemes based on bright field [15] and dark field [16] techniques as well as modifications of grating techniques [17], and even off-axis prealignment with laser interference controlled stepping [18]. The variety of alignment techniques presently being tried is indicative of the poor understanding of the alignment problem. The role of the alignment mark shape (3 dimensions), resist pile up and interference effects of thin film overlays confuse mark design. The tradeoffs in selecting the alignment wavelength, bright or dark field imaging, or alternatively grating techniques are so complex that as yet no standard approach can be predicted.

All of these approaches depend on the quality of the signals diffracted from wafer marks and the imaging of the optics which collect and process the signals. The basic properties of the signals diffracted from wafer marks can be explored using either simple physical approximations or, if necessary, rigorous electromagnetic methods such as used in the analysis of diffraction gratings [19]. The effect of the signal collection optics can be assessed through suitable modification of

simulation algorithms such as those used for imaging mask patterns on wafers [4]. The problems which may be attacked with this array of analytical tools includes: (1) signal quality from typical IC process alignment marks, (2) design of optimum alignment marks (3) understanding of alignment time and accuracy tradeoffs in bright field imaging vs dark field imaging, vs grating alignment techniques.

Alignment in electron beam direct writing systems is potentially considerably more accurate, but still presents rather formidable problems. This is particularly true for production use where wafer marks are restricted to be process compatible and are frequently overcoated with resist. Typical production alignment mark signals in the presence of resist coating have been studied experimentally [20]. Theoretically, Monte Carlo techniques have been extended to non-planar topography and used to a limited extent to examine backscattered electron signals from alignment marks [21,22,23,24]. It has also been found that for selective etched silicon alignment marks that the total backscattered energy signal can be characterized by means of a simple universal curve [23,24]. There is still, however, a pressing need for more complete basic data on the angular distribution of backscattered electrons from various wafer marks and especially for a tractable means of modeling these results.

The key issue in both optical and electron beam alignment is overall system performance. A typical measure of performance is the signal to noise ratio which in turn determines the feedback data rate. Since signal strength as well as alignment signature quality must be considered, this leads to some interesting design tradeoffs. For example in optical lithography, dark field alignment produces a higher quality signal signature but only at a much reduced level compared to the clear field approach. Similarly in electron beam lithography, higher quality signatures are available from collecting only the electrons which exit the substrate at near grazing angles but the number of these electrons decreases rapidly with the angle. The role of the wafer mark properties and electron collection system on the resultant signal to noise ratio can be a dominant factor in the optimization of overall system performance. In both optical and electron beam lithography there is a need to understand the alignment process in terms of models which can characterize these signal generation and collection tradeoffs. Thus there is a critical need both in optical and electron beam lithography to include the generation and collection of alignment signals into system considerations in optimizing overall performance.

Progress

An apparatus for making in situ measurements of resist film thickness during development or etching has been constructed. It is based on monitoring the reflectivity at 6328 Å which varies with thickness change due to interference. Initial results based on data reduction with a hand calculator to extract the etch rate vs. photoactive concentration show that it is possible to distinguish between different batches of the same resist.

An extensive Monte Carlo and experimental study of alignment signals from tapered Si steps, including resist coating, has been completed. Fundamental aspects of the electron scattering distribution in energy, space and angle both within the wafer and in the backscattered signal were investigated. The results are described in Y. C. Lin's Ph.D. thesis, and the following three papers.

Y. C. Lin, "Alignment signals from electron scattering near an edge for electron beam microfabrication," Ph.D. thesis, University of California, Berkeley, March 1981.

Y. C. Lin, A. R. Neureuther and I. Adesida, "Alignment signals from Si tapered steps for electron beam lithography, J. A. Phys., to be published.

Y. C. Lin and A. R. Neureuther, "Alignment signals from resist-coated marks for direct wafer writing," IEEE Trans. on Electron Devices, to be published.

Y. C. Lin, A. R. Neureuther and W. G. Oldham, "Alignment signals from symmetrical silicon marks for electron beam lithography," Kodak Microelectronics Seminar, Interface 1981, October 15-16, 1981, Dallas, Texas.

Significant Accomplishments

A set of guidelines for designing e-beam alignment marks, including resist coating effects, has been established.

An apparatus for in situ measurements of development rate vs. thickness has been constructed using an interferometric technique and is suitable for characterizing optical, e-beam, x-ray and ion resists.

Proposed Research

Characterization of the Limits of Resist Performance

The in situ development rate system will be significantly upgraded and used to quantitatively study development effects for a variety of lithographic applications such as ion, e-beam and x-ray exposure. The apparatus will be augmented so that controlled and reproducible experimental conditions can be obtained. Especially important parameters are the developer flow rate and temperature. Puddle, tank, agitation and flow types of developing conditions will be emulated. Automatic data reduction for extracting the etch rate vs. chemical concentration of photoactive compound in optical resists will be developed. The system will be used to make characterizations of ion, e-beam and x-ray resists. Here the emphasis will be on studying second order effects beyond the simple etch rate vs. dose model.

The exposure and development measurement tools will be used to establish resist model parameters of practical interest and to characterize changes in these as a function of processing parameters and resist modifications. Several examples of current interest are the behavior of AZ1350J in strong (351) and organic developers and the change in the characteristics for the new striation free version (AZ1450). The properties of AZ1350J used as a negative resist by means of image reversal are also of key interest. The modification of the model parameters inherent in process steps such as post exposure baking or the addition of adhesion promoters will also be explored.

To more clearly determine the practical limits of lithographic performance we will establish the relationship between the resist model and performance, assess the capability of various resist technologies, and explore other basic limiting effects. The importance of the resist model parameters on performance will be studied to obtain feedback as to which parameters are significant and how they might be optimized. For example, the standing wave effects can be suppressed to some extent through appropriate modifications of the absorption parameters. An investigation of new lithography strategies such as multilayer and inorganic resists with plasma development will be made to assess from a practical point of view their potential improvement in lithographic performance. Other basic effects such as thermal degradation and blistering which may limit the exposure intensity in serially exposed optical steppers and e-beam systems will also be explored.

Optimization of Alignment Signals for VLSI

Methods of characterizing the effects of wafer mark properties and signal collection optics on optical alignment signal signatures will be explored. The quality of signals diffracted from wafer marks will be considered by simple approximate physical methods and by more rigorous diffraction grating integral equation numerical analysis techniques [18] if necessary. The effects of the optics used in the collection of alignment signals will be simulated through the extension of the image capability of program SAMPLE [4]. This composite set of analytical tools will be used to understand the role of the mark illumination, mark shape, imaging approach and detector in the context of the entire alignment system.

Various optical and electron beam alignment schemes will be examined from an overall system point of view. Particular emphasis will be given to the role of the models for the generation of alignment signals from alignment marks and for the effects of the signal collection system. The signal to noise ratio and other performance figures of merit will be evaluated and used in comparison studies. We will attempt to identify optimum alignment mark features and signal collection system parameters for the dark field, clear field and grating type alignment approaches. Similarly, for electron beam systems we will attempt to

optimize the alignment mark shape and collection angles. Special emphasis will be given to the problem of the degradation of system response with resist overcoating of the alignment marks.

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: SSD-82-2

Last Year's No.(s): SSD-81-2

Title: Study of the Effects Limiting Realization of Far-Submicron Superconductive Electronic Structures

Senior Principal Investigator(s): T. Van Duzer

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Scientific Objective

The objective of this work is to investigate the fundamental factors that limit the size of superconductive devices and circuits.

State of the Art

There is currently interest in two fields that appear destined to converge. Electron-beam lithography has made possible the fabrication of devices and circuits having feature sizes on the order of 0.1 micrometer and smaller. A parallel development is the demonstration of the potential of systems using Josephson junctions as the active elements¹. In some cases the two fields have already met. This has largely been in the formation of very small weakened regions between two larger sections of superconductive material to form Josephson junctions. Some very small-area tunnel junctions have also been made². To date, no work has been reported on theoretical or experimental examination of the effect of making circuits such as memory cells or logic circuits in which all feature sizes approach the characteristic lengths that appear in the theory of superconductivity. These characteristic lengths are called the "penetration depth" and "coherence length." The former is the $1/e$ distance of decrease of magnetic induction from the surface of a bulk superconductor. The latter is roughly the size of the Cooper electron pair, which, in thin films, is largely dominated by the mean free path of the electrons. For superconducting loops, one often refers to magnetic flux quantization; the loop must contain an integral number of flux quanta. For loops of small cross section, the quantization is of the so-called "London fluxoid." If circuits are made with films of 0.1 micrometer line widths, quantization must be considered in the latter terms.

Tunnel junctions have so far been the most common active element in logic circuits and would form a part of this study. Our group has reported the use of semiconductor-barrier devices that appear to have promise for applications in SQUID magnetometry, millimeter-wave detection and mixing, and digital circuits. No consideration in depth has yet been given to the effect of reducing the dimensions of these structures to the 0.1 micrometer size range.

Progress and Publications Since Last Major Proposal

Our device-fabrication efforts under other sponsorship have involved the realization of structures in which far-submicron (approximately 0.1 micrometer) features are required to obtain Josephson effects. These have included constricted-thin-film devices and a structure in which an interrupted superconductive film strip lies on a highly doped silicon surface. We have also developed a strong base for numerical analysis of the properties of superconductive devices and circuits. We have developed the technology of making resist-patterned oxide-barrier junctions and circuits and can work on extending it to the far-submicron range. In addition, a paper entitled: "Silicon-coupled Josephson Junctions and Super-Schottky Diodes with Coplanar Electrodes," by R. C. Ruby and T. Van Duzer will appear in the 1981 IEEE Trans. on Electron. Devices. An abstract follows.

Superconducting devices with coplanar electrodes have been fabricated using electron-beam lithography to define the smallest feature. The devices each

consist of two Pb-In alloy electrodes, 20 μm wide, deposited on a clean, degenerately-doped silicon substrate. The two electrodes are separated by a thin (100-300 nm) gap. Electron-beam lithography is used to define the gap, and sputter-etching to remove the underlying alloy film. Depending on the width of the gap and the condition of the metal-semiconductor interface, these devices displayed either Josephson or super-Schottky diode behavior. The Josephson devices show a high degree of robustness and had $I_C R$ products in the range 200-800 μV at 4.2 K. The super-Schottky diodes had current sensitivities S in the range 1000-1300 V^{-1} when measured at 4.2 K.

This paper reports research sponsored in part by JSEP.

Publications Without JSEP Support

"Hillock growth on lead films upon cycling to cryogenic temperatures," C.Y. Fu and T. Van Duzer, J. Vac. Sci. Technol., 17, pp. 752-754, May/June 1980..

"Josephson digital devices and circuits," T. Van Duzer, IEEE Trans. Microwave Theory and Techniques, MTT-28, pp. 490-500, May 1980.

Government Scientific Contacts

The principal investigator instigated the initiation of a biannual workshop on Josephson digital circuits and was its first chairman. This workshop brings together the governmental, academic, and industrial groups working in this field. He was also elected as vice-chairman of the Applied Superconductivity Conference in 1980. Both of these relationships bring him extensive interaction with scientific personnel from the Office of Naval Research, the Naval Research Laboratory, the National Bureau of Standards and other governmental agencies.

Significant Accomplishments

The work during this period concentrated on verification of the coupling mechanism and improvement of the fabrication techniques for the Josephson device consisting of an interrupted superconductive film on a degenerately doped silicon surface. Devices were made on a checkerboard of doped and undoped areas. The fact that none of the devices on the undoped areas marked helped to establish that the coupling is, indeed, through the silicon and not through strands of unetched superconductor in the gap. It was also possible to prove conclusively that the features seen by SEM in the gap between the superconductive regions are etched in the silicon and are not metallic. Electron-lithographic procedures and ion-milling techniques were developed to achieve greater control of the etching of the gap.

Proposed Research Program

We will conduct studies to determine the feasibility of fabricating useful superconductive electronic devices with feature sizes in the far-submicron size range. We will have a new electron-lithography system with capability of registering one layer to the one below it. With this we can make, for example, logic gates and memory cells. Under other sponsorship, we have developed the technology for making such circuits in larger size. Some of the techniques used in the larger size devices will be usable in the smaller sizes only with considerable effort. Others must be replaced entirely. For example, the present method of

using a silicon monoxide mask to define the size of the Josephson junctions will probably have to be replaced or realized in an entirely new way.

In addition to the fabrication innovation required for these sizes, important questions of physics of the devices must be attacked. The line widths will be on the order of the penetration depth and some features will be comparable with the coherence length. In which situations are these lengths going to set limits on operation? For example, the paired-electron-fluid characteristic of superconductors has a significant amount of inertia and this acts like an inductance. This inductance can be useful in some circumstances, but could set performance limits in others.

Analysis of the behavior of these devices, taking account of the new physical effects that arise because of the sizes being comparable with the superconductor characterizing parameters, will be carried out with our new simulation programs. It will be possible to handle distributed effects as arrays of lumped elements to get accurate representation.

Interaction with Other Work Units

This program of studying miniaturization forms a part of a larger effort on various aspects of Josephson digital circuits. A program has been initiated to develop a high-speed A/D converter and this will use Josephson junctions and circuits of conventional size that can be made by photolithography. In that work, we expect to demonstrate superconductive integrated circuits containing some tens of Josephson junctions. We also have an NSF-sponsored project to study the use of coplanar junctions (both electrodes are in the same plane) with special emphasis on a structure we developed here that involves electron-pair coupling through a highly doped surface of a semiconductor. These may prove to be valuable for miniaturization and that aspect will be considered.

Our work on Josephson devices and their frequent need for submicron dimensions has given our group a high degree of familiarity with electron lithography and we have published several papers in that field. This expertise will be supported by the microfabrication interest of Professors A. R. Neureuther and W. G. Oldham, as well as the large body of knowledge in our integrated circuits group (SSD-83-1).

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: SSD-82-3

Last Year's No.(s): SSD-81-3

Title: New Techniques for Wide-Dynamic-Range Signal Processing
Using Monolithic Integrated Circuit Technology

Senior Principal Investigator(s):	R. W. Brodersen	(415) 642-1779
	P. R. Gray	2-5179
	R. G. Meyer	2-8026
	D. O. Pederson	2-3539

Scientific Objective

To investigate new techniques for signal processing with maximum dynamic range using monolithic integrated-circuit technology. The project will encompass noise characterization, system design, new circuit topologies and a coordinated program of technology research.

State of the Art

Monolithic integrated-circuit technology has profoundly affected the field of signal processing. Functions such as A/D and D/A conversion¹, filtering², and digital signal recovery³ are examples where monolithic technology has become the preferred method of realization in many systems. However, the prevailing approach to the design of such systems is the selection of an arbitrary available technology, often developed for other purposes, followed by research into methods of realizing the desired function.

Our research has shown the need and the potential for a more unified approach to the realization of signal processing circuits which maximizes the advantages inherent in monolithic fabrication. For example, several methods of monolithic filter realization require amplifiers with very high input impedances^{2,4}. These can be realized in such diverse technologies as NMOS, CMOS, BiMOS, BiFET or GaAs and the appropriate technology is not always obvious. In addition, many other critical device parameters have widely differing values in different technologies, providing the designer with an enormous number of potential parameter combinations. These include gm/I and gm/C ratios, parasitic capacitance and many others. These parameters can be varied at the process level if the system requirements are included as inputs at that level.

Progress and Publications Since Last Major Proposal

Our earlier work on the fabrication, characterization and modeling of generalized multi-layer monolithic structures allowed us to realize a unique monolithic process incorporating high-frequency JFET structures with independently-accessible gates. Extensive characterization on a range of devices has been undertaken and verified the advantages of these structures for a wide range of high-frequency signal processing areas. In particular, it appears possible to advance the state of the art significantly in the realization of high-frequency monolithic filters and real-time signal processing. Experimental high-frequency filters using this process are currently in fabrication. These filters incorporate very-wide-band operational amplifiers (unity gain beyond 100 MHz) made possible by the unique JFET structures described previously. This project will continue with further work in combining advanced fabrication techniques and new system concepts with the ultimate goal being the realization of unique methods of high-speed signal processing using arbitrary combinations of analog and digital techniques.

A second aspect of our work has involved new techniques to achieve

maxi possible dynamic range in bipolar and MOS analog amplifiers and signal-processing circuits. Our work in this area has focussed initially on methods of achieving maximum dynamic range in switched-capacitor filters. In such devices, the fundamental limit on dynamic range results from thermal noise in the MOS switch transistors used in the filter structure, but monolithic switched-capacitor filters produced to date have not approached this limit because of the dominant effects of flicker noise in the MOS transistors making up the operational amplifiers^{2,5}. Our research has resulted in a new differential chopper-stabilized technique which removes this $1/f$ noise, resulting in experimental fifth-order filter prototypes with dynamic range in excess of 105 dB. This is more than 15 dB higher than previously reported performance obtained from such filters⁶. We expect to continue this work with the objective of exploring the maximum theoretical dynamic ranges achievable, and formulating detailed theories of the noise performance of such filters.

Significant Accomplishments

- (1) A new high-frequency bipolar monolithic process has been devised and extensively characterized for both low-frequency and high-frequency parameters. This research has led to new circuit configurations for high-frequency monolithic filters, switches and amplifiers which are currently being fabricated.
- (2) A new chopper stabilized differential filtering technique was developed, and a monolithic prototype fabricated. This prototype has been extensively characterized, demonstrating dynamic range and power supply rejection performance well beyond any previously published levels. An extensive theoretical analysis of the sources of noise in switched capacitor filters has been carried out, resulting in a better understanding of the fundamental limitations on dynamic range as a function of energy storage element values. These results have been subsequently applied to the bandpass case, with important conclusions regarding the dynamic range of high-Q bandpass filter structures.

A. Publications under JSEP

D. J. Allstot, R. W. Brodersen and P. R. Gray, "MOS switched capacitor ladder filters," IEEE J. Solid-State Circuits, vol. SC-13, no. 6, Dec. 1978, pp. 806-814. Received the 1980 IEEE W. R. G. Baker Prize Paper Award.

S. K. Lui and R. G. Meyer, "High-frequency bipolar-JFET- I^2L process," Digest of Technical Papers, 1980 International Electron Device Conference, Washington, December 1980.

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K. C. Hsieh and P. R. Gray, "A low-noise chopper stabilized differential switched capacitor filtering technique," Digest of Technical Papers,

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P. R. Gray, R. W. Brodersen, D. A. Hodges, T. Choi, R. Kaneshiro and K. C. Hsieh, "Some practical aspects of switched capacitor filter design," Digest of Technical Papers, 1981 International Symposium on Circuits and Systems, Chicago, April 1981.

K. C. Hsieh, P. R. Gray, D. Senderowicz and D. G. Messerschmitt, "A low-noise switched capacitor filtering technique," IEEE J. Solid-State Circuits, December 1981.

Publications under Other Sponsorship

S. K. Lui, R. G. Meyer and N. Kwan, "An ion-implanted sub-surface monolithic Zener diode," IEEE J. Solid-State Circuits, vol. SC-14, no. 4, August 1979, pp. 782-784.

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Proposed Research Program

The research described above on high-frequency monolithic structures has shown the benefits of combining research in advanced fabrication techniques and new system concepts in a coordinated approach. We propose to continue this research by concentrating on new methods of high-frequency signal processing using high-frequency monolithic structures. Our present work on high-frequency filters will be extended to examine the possibility of filters operating beyond 100 MHz and the process requirements to achieve this end. The initial vehicle will be high-frequency silicon technology, but the results obtained should have implications beyond this to other technologies such as GaAs.

Specific problems to be addressed include choice of optimum circuit configurations and identification of process parameters with maximum impact on ultimate circuit performance. For example, fast settling amplifiers are required and the form of circuit used is closely related to device parameters such as f_T , g_m and parasitic capacitance⁷. These parameters are all process-dependent and it is not yet apparent which of these is the most important. Thus both process research and circuit research are essential parts of the overall program.

During the first year of this program, our understanding of noise mechanisms in switched capacitor filters has greatly improved. We now are able to predict a priori the noise behavior of switched capacitor filters once the device noise parameters are known. We are now extrapolating these results to attempt to draw general conclusions regarding noise limitations in high-Q bandpass switched capacitor filter applications. These filters will become quite important in high frequency communications applications. We are currently fabricating a number of prototypes of such filters which will allow us to compare our theoretical results with experimental observations.

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: SSD-82-4

Last Year's No.(s): SSD-81-4

Title: Research on Electronic Systems Composed of Polymer
Films and Planar Si Devices for Transducer Applications

Senior Principal Investigator(s): D. W. Hess
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Scientific Objectives

We propose to investigate the technology for, and the chemical and physical behavior of electronic systems that are composed of polymer-film materials and integrated-circuit devices. The objectives are to define the materials and interface properties and to evaluate the technologies that may ultimately find application in new and improved transducer devices.

Major Task:

Investigate the control of piezoelectric properties in poly-vinylidene fluoride and poly-acrylonitrile that can be achieved with plasma-based techniques. The purpose of this effort will be to develop novel methods for the production of piezoelectric polymer thin films directly from monomer sources, thereby eliminating many of the constraints inherent in incorporating such films into solid state devices. This study is based upon current work in our laboratory which demonstrates the feasibility of preparing films of vinyl polymers from monomer sources.

State of the Art

The above task is proposed in order to apply newly developed polymer formation technology ^{1,2} to poly-vinylidene fluoride, a polymer material that has very interesting and useful piezoelectric properties ^{3,4}, and to poly-acrylonitrile. Plasma polymerization ^{1,2} techniques have been demonstrated for certain vinyl monomers in bulk condensed phases, but has not been attempted for thin film formation. Our experience with piezoelectric films, particularly with ZnO, has given us a background in exploitation of this property in novel transducers. We expect to show that the plasma polymerization processes can permit tailoring of the piezoelectric activity of the film in order to optimize certain transducer behavior.

Progress To Date

Two systems capable of forming polymer materials from monomer sources have been fabricated. The first system is a glass vacuum rack suitable for plasma initiating liquid monomers ^{1,2}. This system is being used to polymerize acrylonitrile.

The second system is a plasma flow reactor which operates at low pressure (<5 torr). Radio frequency electrical power excites a glow discharge in the monomer vapor, and polymer films are deposited directly on substrates.

In order to characterize these piezoelectric-polymer films, a thermally stimulated discharge (TSD) spectrometer has been built ⁵. This technique measures current resulting from de-polarization of polymer films. These data are used to determine the amount and mechanism of charge storage in polymer films.

Significant Accomplishments

Studies in our laboratory have demonstrated the feasibility of plasma-initiating acrylonitrile. Apparatus for thermally stimulated discharge spectroscopy of polymer films and a special poling device for liquid films have been fabricated.

Update of Current Period

Polyvinylidene-fluoride powder (Aldrich Chemical Company) has been dissolved in dimethylacetamide and methylethylketone, and films have been formed by spinning from solution onto silicon wafers. Aluminum electrodes have been evaporated on the samples, and the films have been poled at electrical fields of 1 megavolt/cm. These poled films are currently being evaluated using TSD analysis. These films will serve as standards for the comparison of properties of plasma formed films.

A special sample holder that will allow films to be poled during polymerization has been designed and fabricated. The holder consists of two parallel electrodes, whose spacing can be varied, and is sealed to prevent monomer from evaporating. A monomer film is plasma initiated and an electrical field is applied across the electrodes to pole the film during polymerization.

Proposed Research

The overall goal of this research is the investigation of process techniques suitable for the production of piezoelectric polymer transducers with high piezoelectric activity and long-term stability. Plasma polymerization techniques appear to offer a novel fabrication method for forming such films. Ultimately, we intend to develop a predictive model that will be useful in optimizing polymer properties for specific transducer applications.

Molecular dipole orientation is considered a primary factor affecting piezoelectric activity. Physical properties such as polymer length, molecular weight distribution, and the amount of polymer chain cross-linking may all influence dipole orientation. These physical properties can also affect polymer chain relaxation, which may be important in maintaining stable piezoelectric activity.

Plasma polymerization techniques offer the ability to vary a number of processing parameters, e.g., plasma power and duration, monomer concentration, and substrate temperature. It has been found that certain combinations of these processing variables can produce extremely high molecular weight linear polymers with a relatively monodisperse molecular weight distribution^{1,2}. Preliminary studies will determine how changes in processing variables affect the physical properties of the polymer films. Once these dependencies are established, polymer films can be produced covering a wide range of physical properties. The polymers will then be further characterized as functions of their piezoelectric activity.

In addition to producing polymers with unique physical properties, plasma polymerization techniques offer the distinct advantage of allowing monomer films to polymerize in the presence of an electrical field. This feature will be exploited in an attempt to align molecular dipoles in the monomer films as polymerization proceeds. Such procedures may eliminate the current requirements of stretching and poling operations needed to impart piezoelectric activity to polymer films.

Piezoelectric activity will be determined using optical techniques to measure the thickness change of polymers during excitation by an electrical signal.

Additional analytical techniques will be used to characterize the various polymer films. Molecular and crystalline structure and composition will be investigated using infrared and x-ray spectroscopy. Charge storage mechanisms will be studied using the previously described thermally stimulated discharge system.

Some investigators have concluded that surface polarization and charge carrier injection from the electrodes is important in determining piezoelectricity in polymer films ⁶. This hypothesis will be tested by depositing polymer films on silicon substrates and metallizing the opposite side of the polymer film. The capacitance and/or the current in the resulting semiconductor-polymer-metal composite will be measured as a function of applied voltage. Such studies will be used to determine charge conduction mechanisms and interface properties of the piezoelectric polymers.

The measurements of piezoelectric activity, polymer physical properties, and charge conduction mechanisms will finally be integrated to form a predictive model. The ultimate utility of this model will be to identify the important polymer properties and processing conditions needed to produce optimum polymer films for various piezoelectric transducer applications.

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

III. Basic Research in Quantum
Electronics and Optics

Coordinator: Professor S. Schwarz

General

We propose to perform research in quantum electronics in the following areas: (1) novel and complex semiconductor laser radiation sources, and (2) analysis, comparison, and evaluation of novel infrared/millimeter-wave radiation detector systems.

At present, semiconductor lasers, though well-advanced, are still unable to perform efficiently as components in coherent, single-mode optical communication systems. Single-mode operation and tunability are difficult to obtain. In part 1 of this proposal we discuss new methods for solving these problems through the use of structures more advanced than the Fabry-Perot resonators used at present. We expect that the proposed structures will also facilitate combination of several interacting lasers into networks. If successful these ideas may bring about significant increases in the usefulness of semiconductor lasers for a large number of scientific purposes.

Radiation detection in the infrared/millimeter-wave region of the spectrum is important for scientific, astronomical, defense, and communications uses. At present our ability to utilize this portion of the spectrum is rather poor --- at both lower frequencies (microwave) and higher frequencies (optical) technology is much more advanced. One reason for this is that neither conventional microwave nor optical devices lend themselves well to this wavelength region. However, several interesting new devices show considerable promise: these include cryogenic Josephson and SIS junctions, metal-barrier-metal (MBM) junctions, and planar ("surface-oriented") Schottky diodes. Part 2 of this proposal is concerned with comparative development and assessment of these novel devices, as components for detection systems. One expects that some devices will be better-suited to some applications while other devices are better suited to others, but the concept of "well-suited" is not a simple one. It involves tradeoffs between possibly competing advantages such as noise-equivalent power or noise temperature, conversion efficiency, bandwidth, response time, frequency of operation, durability, cost, and compatibility with other components. We propose to continue our comparative study of the principles and potentialities of these new devices. Because in some cases the devices themselves are not well understood or seem susceptible to improvement, the systems research will be supported as necessary by basic physical device studies and efforts at fundamental device improvements. It is hoped that the results will allow us to designate the most promising approaches. We then plan to fabricate and test prototypes of the most promising detection systems, in order to verify our conclusions and bring them to the attention of other scientists who can use them.

University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: QE-82-1

Last Year's No.(s): OE-81-1

Title: Functional Analysis of Novel Semiconductor Lasers from an Integrated-
Optical-Network Viewpoint

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Scientific Objectives

We propose to explore and to study novel and complex semiconductor-laser structures for tunability and traveling-wave operation. Theoretical analysis based on scattering-matrix formulation will be carried out to gain insight on possible modes of oscillation in complex laser structures and to guide us in the search for new laser structures. Experimental techniques using LPE and MBE will be developed to fabricate the various structures. Our objectives are (1) to advance the semiconductor-laser technology beyond its present state as an individual coherent optical source, (2) to explore new modes of operation for a semiconductor laser other than the simple Fabry-Perot mode, and (3) to study laser performance when interacting with other lasers or an integrated-optical network.

State of the Art

In recent years important advances in semiconductor lasers have been reported in the attainment of linear light-output versus input-current relation, stable transverse and lateral mode pattern, and single longitudinal mode operation. Equally impressive are achievements in guided-wave optical circuit elements such as directional couplers, switches and modulators. However, except for some interesting work on arrays^{1,2} most of the research efforts on semiconductor lasers and waveguide optical elements have been limited to the performance and characteristics of individual devices. To expand the usefulness of these devices and to explore the potential as well as limitations of integrated optics, these devices must be studied in the frame of an optical network. We believe that it is opportune to apply the knowledge accumulated and the techniques developed for the microwaves to the advancement of guided-wave optical systems involving sources and other optical elements.

One major advance in semiconductor-laser technology is the incorporation of two-dimensional waveguiding in the transverse plane of the laser structure. During the past few years, many lasers exhibiting stable transverse and lateral mode pattern and single longitudinal mode operation have been developed at several laboratories. These include the buried-heterostructure (BH) laser^{3,4}, the channeled-substrate-planar (CSP) laser^{5,6}, and the laser utilizing thickness variation in the grown layer to provide waveguiding in the lateral direction⁷⁻¹⁰. Among the lasers referenced here are the IRW laser⁷, the CJSF laser⁷ and the narrow DCC-CSP laser⁶ being developed and studied in our laboratory. All the lasers mentioned above oscillate in well defined cavity modes in all three directions, transverse, lateral, and longitudinal. This fact facilitates the application of waveguide-network theory to semiconductor lasers and makes possible an analysis of laser structures more complex than the simple Fabry-Perot structure which has been almost exclusively employed in the semiconductor lasers thus far.

In the meantime, remarkable progress has also been made in the fabrication and control of modes in optical waveguides. Low-loss, single-mode waveguides have been reported in GaAs¹¹ and LiNbO₃¹², and active waveguide devices using coupled guides and Y junctions either alone or in the Mach-Zehnder interferometer configuration have been

developed. These advances further support our view that single-mode guided-wave technology is ready for the exploration of new and complex semiconductor-laser structures and the development of simple integrated optical systems involving the source and other optical elements. On the other hand, when semiconductor lasers are used in practical systems such as in conjunction with optical fibers, practical problems, such as induced pulsation in the laser output, do arise. The problems caused by feedback are well known in network theory. Therefore, it seems timely that we utilize the vast amount of knowledge in waveguide network theory in advancing the state of semiconductor lasers beyond its present state as individual sources and in analyzing and overcoming problems encountered in practical systems.

Much of the theory of microwave networks¹³ is directly applicable, since both microwave and optical networks are distributed electromagnetic systems with waveguide modes acting as input and output ports. The known limitations on scattering-matrix parameters¹³ must be considered as constraints on the system. Optical parallel to most of the passive microwave-network elements --- hybrids, filters, isolators, power dividers --- have been worked out in integrated optic form, but not all in a form directly integrable with the semiconductor lasers. Moreover, new fabrication techniques such as MBE will permit still different configurations of these elements. Elegant theoretical analyses of the behavior of certain specific junctions have been made¹⁴, but again not for all that are appropriate to the specific configurations or fabrication techniques. Thus much remains to be done on the network aspect of this problem.

Progress to Date

Our work on control of mode behavior in semiconductor lasers has come to a successful conclusion. This has resulted in a series of papers (see publication list). Now that we have acquired an understanding of how to achieve lateral-mode stability and single longitudinal-mode operation and have developed the capability of fabricating index-guided lasers which oscillate in a well-defined cavity mode, we can move to a new, and perhaps more exciting phase of our research on combining semiconductor-laser technology and waveguide-network techniques (developed for microwaves) for exploration of this relatively unexplored area.

A program of theoretical study has been initiated in the use of scattering-matrix formulation to analyze the proper modes of several complex laser structures and to explore possible new applications for semiconductor lasers. The laser structures investigated thus far include (1) a laser with two coupled cavities in tandem, (2) an interferometer laser with a curved branch waveguide attached to a straight Fabry-Perot cavity, and (3) a ring laser with a straight waveguide attached to a circular cavity. The results of the analysis are summarized in two papers: (1) "Novel semiconductor lasers for integrated optics," which will be presented at the 81 SPIE symposium to be held in Huntsville, Alabama, Nov. 16-19, 1981, and (2) "Studies of semiconductor lasers of the interferometric and ring types" which has been submitted to IEEE J. Quantum Electron. for the special issue on Guided-Wave

Technology. A brief summary of the results is given below.

For the two coupled-cavity lasers, the tandem-cavity laser and the interferometric laser, the longitudinal modes of the composite cavity can be classified into two groups: (1) the coincidence resonance modes (CRM) for which the longitudinal modes of the individual cavities are at resonance simultaneously, and (2) the nonresonant modes (NRM) for which the longitudinal modes of the individual cavities are off their respective cavity resonance. For the CRM's, the threshold gain needed for lasing action is a minimum, and one of the CRM's closest to the gain peak is expected to lase. The CRM's are few in number and thus far apart in wavelength. In between two CRM's lie many NRM's. The coincidence-resonance condition for the tandem-cavity and the interferometric laser provides a built-in selection mechanism for the longitudinal modes. As a result, the lasing wavelength for both lasers is expected to be less sensitive to temperature changes than that of a simple Fabry-Perot laser. Potential applications include wavelength tunability, controlled wavelength switching, and FM operation.

For the ring laser, we have analyzed several possible combinations of the straight and circular guides, and found one combination which offers very interesting possibilities. Our analysis shows that in this particular combination of having $R = 0$ at one of the straight guide's facets, it should be possible (1) to operate the ring laser predominantly in one circulating mode in spite of the existence of internal reflections in the circular cavity, and (2) to minimize the feedback effect on the dominant circulating mode by properly balancing through mutual cancellation the various feedback-induced fields taking different optical paths.

The initial set of experiments on both the interferometric and the ring laser has been carried out and has confirmed some of the theoretical predictions. For the interferometric laser, widely separated lasing modes have been observed which can be attributed to the simultaneous lasing of two CRM's. The lasing wavelength changes with temperatures at a rate of $1\text{\AA}/^\circ\text{K}$ as compared to a rate of $3\text{\AA}/^\circ\text{K}$ for simple Fabry-Perot lasers. For the ring laser, we are working with several waveguiding structures to improve our previous results¹⁵. LPE growth over etched curved channels is in progress. We believe that the inverted-ridge curved guide has much smaller scattering loss than the high-mesa curved guide used in our previous experiment.

In addition to the optical waveguide networks fabricated on the semiconductor chip, we have also considered the potential of coupling from the laser to a different material to support the network. This might be to a fiber junction, but we are now concentrating on LiNbO_3 since waveguiding techniques in this are well developed¹⁶, and the significant electro-optic effect allows phase control for tuning, phase locking, or the other functions being studied. Probably the best developed guiding technique is that of titanium diffusion which has been used in our laboratories for modulators¹⁷. We are thus planning some networks of this type. But in addition, we are also reviewing the very simple slot line first demonstrated by Channin¹⁸ in which the electro-optic effect provides the index change for guiding. Exact analysis of the modes in this is quite complicated since the guiding region is both

inhomogeneous and anisotropic, but an approximate analysis by Chiao and Das¹⁹ has shown Laguerre-exponential mode forms with good confinement with reasonable gap sizes and voltages. Comparisons of the two guides will thus be made, although it may be that a combination is preferable to either alone.

Publications Under Combined Sponsorship

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Significant Accomplishments

A major effort in the past was devoted to a study of the mode-stability problem in semiconductor lasers, and our work was summarized in an invited paper, "Control of Mode Behavior in Semiconductor Lasers" published in IEEE J. Quantum Electron. In brief, we showed that a lateral index difference as small as 10^{-3} should be sufficient to stabilize the lateral mode. Many laser structures, including the IRW laser, the CJSF laser, and the DCC-CSP laser developed in our laboratory satisfy this index-difference requirement. We also demonstrated in the experiment with the DCC-CSP laser and the TEPOSE laser (see publication J. Appl. Phys., 52, 614, 1981) the importance of a uniform and symmetric carrier distribution. It is essential to keep any carrier-density variation below 10^{17} cm^{-3} in order to maintain lateral-mode stability in weakly index-guided lasers.

The effect of a nonuniform current distribution on the longitudinal mode behavior was also discussed. From the spectral gain curve

calculated by Stern, we estimated a spectral broadening of 15\AA for a nonuniformity in carrier concentration by about 10^{17} . Note the value of 15\AA is much larger than that of longitudinal mode spacing. Therefore, a uniform carrier distribution is also very important to single longitudinal mode operation.

In summary, we have shown that a uniform carrier concentration is a key element, in addition to a built-in index difference to lateral-mode stability and single longitudinal mode operation in semiconductor lasers. To ensure a uniform carrier concentration, the effects of carrier diffusion and current spreading in a given laser structure must approximately balance the effects of stimulated emission (that is, spatial hole burning) and thickness variation of the region.

Proposed Research Program

As discussed in the State of the Art review, in order to explore new applications for semiconductor lasers and to extend microwave techniques to guided-wave optics, it becomes necessary that we study lasers with complex structures for performing functions other than merely providing coherent radiation. Furthermore, since a laser is only a part of an optical system in practical applications, analytical methods must be developed so that the laser performance can be analyzed in the frame of an optical network.

In spite of the progress made in improving the performance of semiconductor lasers, tunability of the laser wavelength has not been achieved. We propose that the tandem-cavity laser and the interferometric laser be studied for wavelength tunability and controlled wavelength switching. An estimate based on the electrooptic coefficient in GaAs indicates that a tunable range for the laser wavelength in the neighborhood of 4\AA should be possible. For wavelength switching, the range should be much larger, probably on the order of 50 to 100\AA .

Besides tunable lasers, another subject of considerable interest involves coupled lasers in the form of directional couplers. Before coupled lasers can be used to advantage in practical applications, several important questions must be answered. First, it is uncertain whether the lasers, even though coupled together, will oscillate independently or as a whole. Second, if they do oscillate together, the question remains as to whether they will operate in a single longitudinal mode or in multiple modes. Thirdly, it is important to see if distributed coupling gives different performance than coupling through the interconnecting waveguide network. Reflections have been found to have a degrading effect upon performance of semiconductor lasers²⁰. So far coupled-laser experiments have been reported only on laser arrays with every two lasers connected at alternate ends instead of using directional couplers for coupling. Furthermore, the individual waveguide in the array can support many lateral modes. Therefore, the multi-longitudinal mode behavior observed in these experiments could be caused by the existence of multiple lateral modes. We propose that experiments on coupled lasers be performed on waveguides exhibiting a fundamental lateral mode. In our laboratory, we have developed several lasers which are capable of single mode operation^{6,7}. Once we are sure of single lateral-mode behavior, we can extend our analysis based on the

scattering matrix and the coupled wave equation to coupled lasers using directional couplers. The characteristic equation should yield valuable information on the lasing mode or modes.

Another subject which we are currently investigating concerns the possibility of operating a semiconductor laser in a traveling-wave mode instead of a standing-wave mode as in the conventional Fabry-Perot laser. As mentioned in the Progress to Date report, we have analyzed various possible combinations of the circular and straight guides, and found one particular combination very promising. One obvious, and potentially important, advantage is the possibility to minimize the effect of optical feedback on the dominant circulating mode. Such feedback has been the cause for induced pulsation in semiconductor lasers when coupled to an optical fiber. We propose that our present work on the traveling-wave laser be continued. We select the curved inverted-ridge (IR) waveguide for the experimental ring laser structure for two reasons. It can be fabricated by growth over an etched channel, with which we are familiar in fabricating straight IR waveguides. Second it is possible to incorporate reversed biased p-n junction in the laser structure for double current confinement as we did in the DCC-CSP laser. However, for a circular cavity, the index difference must be large enough in order to keep the radiation loss small. This is an important design consideration which needs further work for its implementation.

In continuing the work on external waveguide networks for tuning, phase control and power combining, we will continue the work on LiNbO_3 with a comparison of titanium-diffused guides, slot-line guides and combinations. An improved analysis of the mode structure in the inhomogeneous, anisotropic guides will be attempted. This will start from the simpler models¹⁹ and either utilize perturbation techniques or numerical methods to find the major variations from these.

A major new emphasis will be in considering dispersive effects in the various guides and networks as they are used with pulsed signals. The major use of semiconductor lasers is with digital modulation. High data rate systems now operate with nanosecond pulses, but picosecond²¹ and even subpicosecond²² pulses have been obtained by mode locking these lasers. A great deal of study has been done on the dispersive effects in fibers, but very little has been done on the pulse dispersion for the guides used in integrated-optics networks. Preliminary calculations indicate that it will be a limit for picosecond pulses. Group velocity

dispersion, related to $\frac{\partial^2 \beta}{\partial \omega^2}$ where β is phase constant and ω is angular

frequency, causes pulse spreading and higher derivatives, $\frac{\partial^n \beta}{\partial \omega^n}$ cause

further distortions²³. For single-mode guides, the two contributions to these terms come from materials dispersion and the frequency characteristics of a given mode. For silica fibers around $1.3 \mu\text{m}$, the two contributions to group velocity dispersion cancel but this is unlikely for the materials of the integrated-optic network. For multi-mode guides, the intermode dispersion generally dominates.

Solitons, which are pulses which retain their shape through non-linear mechanisms in the material, have been observed in fibers²⁴, and have in fact been proposed for high data rate communication systems²⁵. It will be interesting to see if such are possible for the integrated optics guides.

Interaction with Other Work Unit

Frequent consultation is anticipated with the work unit on electromagnetics concerning wave propagation in dielectric waveguides.

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University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: QE-82-2

Last Year's No.(s): QE-81-2

Title: Millimeter and Infrared Heterodyne Mixing and Detection

Senior Principal Investigator(s):	T. K. Gustafson	(415) 642-3139
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Scientific Objective

In this project we propose to study radiation detection systems involving direct detection and superheterodyne mixing techniques using various nonlinear devices for mixers and detectors. The wavelength range of interest is the entire band of frequencies from millimeter through far infrared, that is, 10 mm to 10 microns wavelength. It is of particular interest to understand which techniques are favored --- in the framework of realistic receiver systems --- for application in various parts of the frequency range. The investigation will involve coupling of radiation to devices with impedance matching, selection of the best devices and obtaining their characteristic parameters, and a study of optimal coupling to intermediate-frequency amplifiers. Objectives include low-noise receiver performance, plus other advantages such as wideband response and, for some devices, room-temperature operation. The novel devices in question (being developed partially under other sponsorship) include planar Schottky diodes, super-Schottky diodes, cryogenic SIS and Josephson junctions, metal-barrier-metal diodes, and novel configurations of other, more conventional detectors. Attention will be given to principles of coupling to multiple-device arrays.

State of the Art

The noise temperatures of mixer-IF amplifier combinations have been surveyed for the frequency range 1 GHz (wavelengths of 30 cm to 0.3 cm) [1]. Room temperature mixers are usually Schottky diodes in this range and their best noise properties are typified by a measurement by Kerr [2] at 100 GHz; assuming an IF amplifier with a 15 K noise temperature, the single-sideband noise temperature for the mixer-IF amplifier combination is about 550 K. Equivalently, this is a minimum detectable power of 0.76×10^{-20} W/Hz. That value was then further reduced by nearly a factor of two by cooling the diode (essentially the same results are achieved at $T = 18$ K or $T = 77$ K).

To achieve large reductions of noise temperature for frequencies in the several-millimeter wavelength range, superconductive devices must be used. There are two general categories. In one, the Josephson effects are employed, and in the other, the nonlinearity that comes with single-particle tunneling in superconductors. The best results obtained with the Josephson devices have mixer noise temperatures in the range of 20-50 times the liquid-helium bath temperature with conversion efficiencies in the range of 0.5-1.4. Mixer noise temperature of 54 K with conversion efficiency of 1.4 at 36 GHz [3], and 140 K with conversion gain of 2.4 at 140 GHz [4] have been achieved. Opinion now is that the Josephson devices have too much noise down-converted into the IF range by beating of the RF noise with the many harmonics of the LO signal and the Josephson oscillations. Still, Taur estimates from detailed computer calculations that a receiver noise temperature of 70 K should be achievable for a SSB receiver at 100 GHz, assuming an IF amplifier with a 20 K noise temperature [5].

Considerable emphasis is now being placed on the "quasiparticle" (single particle) tunneling devices, also known as NIS and SIS junctions. This has grown out of the realization that very strong nonlinearities of the I-V characteristic are available for classical

resistive mixing through the use of devices that function at millivolt levels where a sharp change of slope results from the existence of the superconducting energy gap. The experimental work has been further inspired by the quantum-mechanical analysis of Tucker [6] showing that an SIS mixer can be expected to give quantum-limited detection sensitivities at high frequencies (>70 GHz). It has also shown that conversion gain can be expected from these devices. The earliest of the quasiparticle devices was the super-Schottky diode, which is a Schottky diode with the metal electrode replaced by a superconductor. These showed the best diode noise temperature ever seen at 10 GHz [8]. In the usual configuration, the series resistance leads to a parasitic conversion loss which increases strongly with frequency so that usefulness of the device is limited to wavelengths longer than several millimeters. In the normal metal-insulator-superconductor (NIS) tunneling device, the Schottky barrier is replaced by that of the insulator, and the series resistance is largely eliminated. The same applies in the case of the superconductor-insulator-superconductor (SIS) junction; in this device, the nonlinearity is stronger but it also has Josephson current which can add noise. Results to date on the SIS and NIS junctions have been excellent [9]. Experiments with SIS junctions at 36 GHz have demonstrated the predicted conversion efficiency. The single-sideband value of 0.7 (or 1.4 in DSB) is greater than can be expected from classical mixing theory. The mixer noise temperature of 3 K (SSB) is very close to the photon noise limit $h\nu/k_B = 1.7$. These experiments were done with lead-alloy oxide-barrier-junctions. It would be advantageous to use a more rugged system such as niobium on thin silicon membranes.

The highest frequency at which the quasiparticle mixers have been reported is 115 GHz where a conversion efficiency of 0.2 and a mixer noise temperature of less than about 80 K were deduced from a receiver noise temperature of 470 K. One part of our work is aimed at making an antenna-coupled mixer at one millimeter wavelength; the first measurements will be at 70 GHz. Carrying the advantages of these devices to the submillimeter wavelength range is a large and important task.

At wavelengths near 10 microns, extrinsic and intrinsic photoconductive and photovoltaic detectors can be used as mixers. Minimum detectable power near the quantum limit (about 10^{-20} watt for 1 Hz bandwidth) has been demonstrated [9,10]. Although results have been impressive, it is difficult to obtain IF bandwidths much larger than 1 GHz with such mixers. Moreover, they all require refrigeration, at least to 77 K. As one goes toward longer wavelengths, mixers are more difficult to make. A detectable power of 3×10^{-16} W at 119 μ using an extrinsic Si mixer and 2 K has been reported [11]; in another experiment with an extrinsic GaAs mixer at 4 K, a detectable power of 10^{-14} watt was reported at 337 μ [12].

In principle, one should be able to do much better than this at wavelengths around 0.1 mm, using resistive diode mixers at room temperature. Minimum detectable powers on the order of kTB , or 4×10^{-21} watt/Hz, are theoretically possible. But results achieved to date fall short of theoretical limits: with Schottky diodes, for example, room-temperature detectable powers of 10^{-9} , 10^{-12} , and 5×10^{-15} W/Hz at 118, 170 and 337 microns, respectively [13,14]. One experiment has also been

done to test the metal-barrier-metal diode as a mixer [14] at 10 microns; the detectable power was 10^{-13} W/Hz at room temperature. This is the lowest value that has been obtained for 10-micron room-temperature detection, but it also far above theoretical limits.

With regard to room-temperature detection and mixing in the 1-3 mm range, conventional Schottky diodes have given good performance. However, there are difficulties with stability, ruggedness, and cost. Presently a new technology seems to be possible, based on the integration of dielectric waveguides and planar (or "surface oriented") Schottky diodes, and perhaps other components, into millimeter-wave integrated circuits. Under other support we are presently studying devices for this purpose. Our work under JSEP relates to the principles and potential capabilities of such systems, especially as compared with the other types of receivers already mentioned.

In summary, progress in infrared/mm detection and mixing in the coming years will involve (a) extension of the nearly quantum-limited sensitivities of superconductive devices as far as possible into the range above 100 GHz; (b) extension of the capabilities of room-temperature devices to wavelengths below one millimeter; and (c) development of efficient coupling schemes and rugged devices.

Progress and Publications Since Last Major Proposal

Work has continued on silicon membrane, sandwich-type superconductive devices which can be made either as Josephson junctions or super-Schottky diodes. These are being made with a two-step etching procedure. First, a membrane of about $50 \times 50 \mu\text{m}^2$ and $3 \mu\text{m}$ thick is made by preferential etching. The boron dopant used to stop the etching is then removed. A new, shallow doping is then done, and a small etch pit is made in the $3 \mu\text{m}$ thick layer. The final membrane is to be about $1 \mu\text{m}^2$ with a thickness of 50 - 100 nm. The reason for using the two-step process is that it is necessary to know the thickness with greater precision than the allowed errors in the dimensions of the final membrane. We can measure the $\approx 3 \mu\text{m}$ -thick layer with some precision. We have had difficulty with spurious etching during the out-diffusion step and considerable effort has been devoted to developing an understanding of the process. Some improvements have been made in the yield. We have also taken the approach of doing the first etching step without a prior doping; the etching control is by timing and visual observation. The membranes thus formed do not have the damage which is a natural concomitant of the heavy doping for the thick membrane; we will seek to determine whether that changes the performance of the device. We have also developed a procedure for nondestructive measurement of the membrane thickness by using the penetration of the electron beam in a scanning electron microscope. We have started to develop a model for the semiconductor-barrier junction. A 90 GHz microwave mixing system has been prepared for testing the devices both as Josephson junctions and as super-Schottky diodes. This work is continuing.

Quasiparticle SIS mixers for the millimeter range are also being developed. Here our approach has centered on unifying the SIS junction with an antenna structure, the latter to provide efficient coupling. A typical design consists of a sandwich-type vee antenna with four SIS

junctions in series at its terminals. Performance approaching theoretical quantum limits is expected near 70 GHz. At higher frequencies the capacitance of the junctions becomes a problem, and a novel method has been developed to tune reactance out (see proposal). With this scheme it should be possible to use the antenna-coupled SIS at frequencies up to 300 GHz. Computer analyses have been used to confirm the basic design. Fabrication of the SIS junctions and associated antenna/transmission line structures is now in progress.

In order to test receivers near this higher frequency, a 230 GHz isotopic methyl fluoride laser has been constructed. The CO₂ pump laser for it is now working well and the FIR laser itself is being perfected.

This JSEP grant has supported some exploratory research with planar Schottky diodes. The design of these diodes has been developed and analyzed. Considered as video detectors, these diodes are expected to have NEP higher than that of non-planar diodes by a factor of about ten. This drawback is compensated by the greater ruggedness and integrability of the planar diodes. Practical development is now being carried on further under non-JSEP support.

We have shown that efficient coupling of radiation at 36 GHz into thin film metal-barrier-metal junctions can occur. Sensitivities within a factor of about three to five of Schottky barrier junctions can be obtained for direct detection at 36 GHz. The noise was $1/f$ limited up to a few tens of megahertz when a bias was applied. The characteristics of this noise spectrum are attributable to impurity noise and can possibly be alleviated by better fabrication of the barrier material. In the absence of the $1/f$ spectrum (high frequency or zero bias), the noise was Johnson or shot in nature.

Heterodyne detection at 36 GHz and harmonic mixing using a 72 GHz signal were also performed. Conversion losses were respectively about ten to twenty db greater than that reported for commercially available detectors. However, an optimum design for the harmonic mixing experiment was not used.

These experiments, the results of which are described in detail elsewhere [15], provide strong evidence that the metal-barrier-metal structure would be superior to Schottky barriers at higher frequencies: frequencies above which the spreading resistance results in inferior performance for the Schottky devices. We have thus initiated a study of the fundamental characteristics of metal-barrier-metal junction structures at shorter wavelengths.

An initial experiment [16] has demonstrated the coupling of 118 μm radiation to an edge metal-barrier-metal structure situated at the center of an eleven wavelength antenna. Although the sensitivity of detection was not high, the coupling principles first suggested by Hwang et al. [17] were established for M-B-M junctions. The edge structure for the junction [18] had an area of $\approx 10^{-10} \text{ cm}^2$ which is comparable to a point contact junction. Thus the RC time constant corresponded to a wavelength much shorter than 118 μm . This initial detection experiment established that coupling to planar junctions is possible and that fundamental investigations of a variety of mixing and detection experiments at shorter wavelengths are possible. To this end small area edge metal-

-barrier-metal junctions having planar linear antennas have been fabricated on a silicon substrate without an intervening lossy silicon dioxide layer. The resistivity of the silicon used was of the order of 1000 Ω -cm so that the junction conduction dominates. The edges of the substrate have been bevelled for the purpose of coupling radiation at an angle, through the substrate, to the planar antenna. The bevelled edge thus acts as a prism in analogy to integrated optical coupling to thin film modes.

A microwave microstrip has also been fabricated to couple the I.F. from the mixer diode to a microwave spectrum analyzer.

Publications

The following papers acknowledged partial or total JSEP support:

- (1) "Characteristics of Integrated MOM Junctions at D.C. and at Optical Frequencies," IEEE Jour. Quantum Elec., QE-14, 159 (1978).
- (2) "Electronic Resonance of CARS," Phys. Rev., 18 (1978).
- (3) "Photo-Induced Currents in Metal-Barrier-Metal Junctions," Radiation Energy Conversion in Space, ed. by K. W. Billman, 1978. (Vol. 61 of Progress in Astronautics and Aeronautics Series.)
- (4) "Coupling to an Edge 'Metal-Oxide-Metal' Junction via an Evaporated Long Antenna," Appl. Phys. Lett., 34, 823 (1979).
- (5) "Small Area Metal-Oxide-Metal Junctions as Picosecond Photoemissive Detectors," in Picosecond Phenomena, Springer Series in Chemical Physics, vol. 4 (ed. by C. V. Shank, E. P. Ippen, and S. L. Shapiro).
- (6) "Moving Toward MM Wave Integrated Circuits," Microwave Journal, 47-52 (June 1980).
- (7) "Progress in MM Wave Integrated Circuits," presented at the Fifth International Conference on Infrared and Millimeter Waves, October 1980.
- (8) "A Phototransistor with Concentric Electrodes on the Si Substrate," IEEE Electron Device Letters, EDL-2, 200 (1981).
- (9) "Characteristics of an Avalanche Phototransistor Fabricated on a Si Surface," Appl. Phys. Lett., 39, 161 (1981).
- (10) "High Speed Si Lateral Photodetector Fabrication over an Etched Interdigital Mesa," Appl. Phys. Lett., 37, 1014 (1981).

The following doctoral thesis was completed under JSEP support: D. C-W Chen, "High-Speed Photodetectors With Interdigital Mesa Structures on Si Surfaces." The abstract is as follows.

Silicon photodetectors were fabricated to convert incident optical radiation into electrical signals. The symmetrical lateral photodetectors devised and studied in this work were made over interdigital mesa structures with areas of 0.5 mm x 0.5 mm using the anisotropic-etching technique.

A brief review of the fundamentals of junction photodetectors is first presented. Concept of the lateral pnp photodetector is then introduced. Detectors with different dimensions were fabricated. The I-V curves were examined and exhibited phototransistor characteristics. Pulsed-light responses were measured with various laser sources. Rise time and FWHM (full width at half maximum) of the impulse response were observed to be 100 ps and 190 ps, respectively. The noise characteristics were also studied.

Finally, the avalanche breakdown mechanism was included to realize an avalanche phototransistor. Characteristics of this novel device were measured and are discussed.

Compatibility with the existing monolithic planar processing makes these detectors interesting for optoelectronic applications.

Significant Accomplishments

We have gained an improved understanding of the processes involved in the fabrication, by the two-step etching procedure, of silicon membrane Josephson devices. Successful devices have been made and tested.

A new approach to tunable quasiparticle mixers has been devised. The novel features of this design are (a) use of an integral planar antenna to improve coupling and (b) use of an electrically-tunable variable reactance to cancel device capacitance.

Metal-barrier-metal structures have been successfully fabricated on a silicon substrate. A microwave I.F. coupling structure has been devised and the lasers are presently being readied for a heterodyne harmonic mixing experiment.

Proposed Research Program

Research on the use of the phenomena of superconductivity in the proposed work for detection and mixing will take three paths. Microfabrication of the silicon-coupled structures will continue in order to improve the control of their electrical characteristics. A new coupling concept in the form of a microstrip-type of electrode arrangement to minimize the effect of the capacitance of the substrate will be evaluated. Devices will be tested as mixers at 36 GHz and 90 GHz to prove the assertion of reduced parasitics. This will give a guide to the frequency limitations of this type of structure so we can evaluate whether it can be used in the submillimeter-wavelength range. The choices of metals will be such as to realize both Josephson and super-Schottky behavior. The superconductor used will, at first, continue to be the lead-indium alloy. One of the virtues of the silicon membrane barriers is that high- T_c materials should make satisfactory electrodes, thus making it possible to fabricate rugged mixers that can operate in the temperature range where small simple refrigerators are available. Thus, the use of such other materials will be studied to see if there are unexpected phenomena.

A theoretical model of the semiconductor barrier Josephson junction will be developed. We have already partially evaluated one proposed model and find that important aspects of the electrical properties are not described. The new work will make use of the phase-slip model that has had success in describing other simpler types of Josephson junctions. The extra complications in the semiconductor barrier structure are that it is physically inhomogeneous, having Schottky barriers at each of the interfaces of the semiconductor with the superconductors and a degenerate region between them.

We also plan to continue with studies of quasiparticle mixers for the 70-300 GHz range. The design we are pursuing, developed conceptually during the last reporting period, will now be described. A planar vee antenna is deposited on a quartz substrate [17]. At its terminals we construct four lead-indium SIS junctions in series. (Four are used to increase impedance, so it approximately matches the antenna source impedance.) A parallel-conductor transmission line (nearly lossless because it is made of superconductor) is constructed in parallel with the set of junctions. At the other end of this line is a larger SIS junction dc biased with an adjustable current less than the critical current. This junction acts as an inductor, whose reactance can be varied by varying the current. This reactance is transformed by the transmission line, and the transformed reactance appears in parallel with the mixer diodes. By adjusting the dc bias current and choosing the size of the tuning junction and length of the transmission line, we expect that the capacitance of the mixer junctions can be canceled. This will allow us to use the SIS mixer at frequencies higher than has been possible until now. If the new design approach is successful it should find important uses, especially in astronomy. Observations of new phenomena should also be possible. In particular, the predicted quantum effects of Tucker [6] should only become observable at frequencies above 100 GHz; our technique for canceling capacitance should allow such observations to be made. Design studies are now complete and fabrication is in progress. Video and heterodyne NEP measurements will be made at 70 and 180 GHz.

A considerable amount of information has been obtained by investigation of the detection characteristics of metal-barrier-metal junction structures. This includes the recent work involving 36 GHz detection [15] using waveguide coupling as well as 118 μm detection utilizing quasi-optical coupling [16]. The 36 GHz work demonstrated virtually 100% coupling of the incident radiation. It also provided verification of detection based upon rectification by the current-voltage characteristic of the junction. The 118 μm detection demonstrated that antenna theory can be applied to the quasi-optical coupling and that slowing of the guided mode along the antenna occurs and must be considered, as pointed out by Hwang et al. [17].

The detection and mixing characteristics of metal-barrier-metal structures are expected to be superior to other devices at shorter wavelengths. In addition, fundamental characteristics of such microstructures can be more amply investigated by utilizing harmonic mixing. We thus propose an investigation of harmonic mixing utilizing the 28 μm output of a water vapor laser and the 9.3 μm band of the CO_2 laser. The IF frequency is in the 20 GHz frequency range and can be detected directly with a high frequency spectrum analyzer. All of these are in hand.

Such a harmonic mixing experiment has been accomplished with point contact metal-barrier-metal structures. It can be argued that this was a direct demonstration that currents flowed across the junction at a frequency corresponding to 9.3 μm and consequently established the fundamental requirement for lumped components at near infrared wavelengths.

No similar mixing has been accomplished with planar fabricated metal-barrier-metal junction structures. The problems are several and provide fundamental reasons for pursuing such an investigation. There is the coupling problem. We wish to use quasi-optical coupling to an

antenna structure at 28 μm , in analogy to work already accomplished at 118 μm . The 9.3 μm radiation is to be coupled through a similar antenna structure. A second problem involves the thermal aspects. The high frequency harmonic mixing signal cannot be thermal; however, there is still the localized heating of the junction to contend with. This can be alleviated by proper choice of the substrate and fabrication of electrode shapes which maximize the conduction of heat away from the junction. A third aspect which is of interest is the possible enhancement of the radiation field in the region of the junction structure by the fabrication of various types of resonance structures at 9.3 μm and 118 μm . Rectangular dielectric resonance cavities are presently being discussed.

Thus far we have been pursuing the microfabrication of edge M-B-M's on a silicon substrate. We plan in the near term to demonstrate direct detection at 28 μm and 9.3 μm utilizing such junction structures. Quasi-optical coupling will be utilized. It is anticipated that electron lithography will eventually be used to fabricate edge junctions with a smaller area (and therefore a smaller RC time constant). Subsequent to the direct detection experiments, the harmonic mixing experiment will be attempted. Of primary interest is the behavior of the IF signal detected as a function of both the bias across the junction structure and the angles at which the radiation at 28 and 9.3 μm are incident.

The results of the mixing experiment will provide fundamental knowledge concerning the basic phenomena responsible for the voltage-current characteristics of such devices. This has up to the present been elusive because of the presence of thermal effects and other low frequency contributions to direct detection. In addition, it will provide information which should be useful relating to the possibility of lumped devices for infrared wavelengths. Finally, the motivation to enhance the coupling, find suitable substrates, and to enhance the fields in the region of the junction are expected to ultimately result in new microstructure approaches to radiative interactions with solids.

Triode-like M-B-M-B-M structures have been considered in some of our earlier work as potential amplifiers or oscillators at millimeter frequencies or higher. Such devices still appear to have promise, and although they will not occupy a major portion of our attention under this grant, we plan to continue exploratory studies insofar as they are related to the work proposed above.

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Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

IV. Basic Research in Information Systems

Coordinator: Professor C.A. Desoer

General

About twenty years ago, the unity of the basic concepts and techniques underpinning the fundamental study of circuits, control systems and communication systems became apparent and became known as system theory. With rapidly increasing power and decreasing cost of computing, these concepts and techniques were applied to larger and larger systems. This commonality of basic theoretical tools and approaches still exists today and as the size of the system under study increases, the nature of the problem changes.

These features are particularly apparent in the first pair of topics which cover respectively large circuits and large control systems. In each of these topics we see a fundamental interweaving of decomposition techniques -- such as diakoptic analysis, graphic decomposition by strongly connected components and minimum essential sets, and decentralized control by creation of a hierarchy --, modeling techniques -- piecewise linear and spline approximations -- and analytical techniques.

The third topic is a bold project aimed at stepping out of the by-now-traditional use of simulation for computer-aided electronic circuit design and reaching for a more sophisticated level where the simulation is coupled with up-to-date optimization algorithms to direct the design toward a minimum of a previously chosen objective function or towards the display of a trade-off curve (or surface), so that the engineer using additional data not present in the mathematical formulation, can choose what he seems to be optimum. A significant feature of the optimization algorithm is that inequality constraints may easily be imposed, a fact which we consider crucial in engineering design.

To anyone who studies these three proposals it is clear that in the course of the work there will be ample opportunities for interaction and cross-fertilization, both through normal informal contacts and through regular seminars.

University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: ISS-82-1

Last Year's No.(s): ISS-81-1

Title: Large-Scale and Nonlinear Circuits Study

Senior Principal Investigator(s):

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E. S. Kuh

2-2689

Scientific Objective

Our objective is to continue our research efforts on large scale and nonlinear circuits which were initiated several years ago. The many tools and results that we have developed so far continue to serve as a foundation for our future research and will be used to attack several interrelated fundamental problems in this relatively unexplored but important area.

State of the Art

Network theory played a major role from the early 40's to the 60's in the development of the present day communication systems. The main thrust of network theory then was directed at the analysis and synthesis of linear circuits which can be characterized by a relatively small number of differential equations. Although in recent years many authors have published papers on nonlinear circuits and large-scale networks, the extent of the development of large-scale nonlinear circuits, both in theory and applications, is nowhere near the kind of maturity in classical network theory. The advances during the past decade in electronic devices and integrated circuits, coupled with the immense impact of computers on circuit analysis and design, have drastically changed the nature of the problems faced by circuit theorists. While analysis of circuits is still the key problem, it is more difficult in view of the size and complexity of the circuit and the inherent nonlinearity which exists in most electronic devices. Furthermore, the scope and significance of "circuit analysis" has been much broadened. Theory and techniques developed from large-scale networks and nonlinear circuit analysis can often be used in other types of large-scale network and system problems; for example, computer networks, power networks and complex control systems.

It should be noted that because of the size and complexity of LSI and VLSI, the objectives and approaches in analysis are considerably different from those of the classical network theory. First, computation becomes a key element in the study of any large circuit or system. The development of efficient algorithms is crucial. While theoretical results are essential, often one must also depend on heuristics. Second, the study of the structure of a large circuit and the property of interconnection is important. Frequently, large problems need to be divided into smaller sub-problems in order to facilitate analysis, data storage and computation. Third, design is usually accomplished by experience as a first step and improved on by repeated analysis. Fourth, such problems as reliability study, tolerance analysis, diagnosis and testing are important and should be kept in mind in the overall design process. The last item constitutes a new area of research which was not a part of classical network theory. All these indicate that there exist a large variety of problems of a circuit-theoretic nature which need to be studied.

Progress and Publications Since Last Major Proposal

The following is a summary of research progress in the area of non-linear and large-scale networks which were published since the last major proposal.

1. Research Progress on Piecewise-Linear Analysis and Piecewise-Linear Algebra

Piecewise-linear techniques have been used extensively in circuits and systems theory to model dc nonlinear characteristics of electronic devices, and to study a large class of nonlinear resistive networks. In 1977, Chua and Kang introduced new analytical representations for one-dimensional piecewise-linear functions¹. This piecewise-linear representation was subsequently generalized to the multi-dimensional case: it is applicable for any m-dimensional piecewise-linear function which is affine over convex polyhedral regions bounded by linear partitions². This generalization results in a tremendous amount of data compression, thereby allowing large-scale piecewise-linear equations to be stored in significantly less computer memory space. Application of this result to the modeling and analysis of large-scale networks is presently under investigation.

A new algorithm has recently been developed for solving piecewise-linear equations of nonlinear electronic circuits.* Unlike other methods, this algorithm guarantees that all solutions will be found in a finite number of steps. The method depends crucially on the above cited development which allows a multi-dimensional piecewise-linear function to be represented in a closed canonical form. This highly compact representation requires only a minimum amount of computer storage and is responsible for the efficiency of the algorithm.

Although motivated originally by analysis problems, the piecewise-linear representation in reference 2 led naturally to important applications in nonlinear circuit synthesis. In particular, systematic methods for synthesizing nonlinear networks having a prescribed scalar or multidimensional piecewise-linear function have been developed³. In the scalar case, precision active-circuit building blocks using operational amplifiers, transistors, diodes, and resistors have been derived for realizing piecewise-linear driving point and transfer characteristic plots. In the multidimensional case, methods have also been obtained for realizing a multiterminal nonlinear network having a multidimensional piecewise-linear transfer function. Moreover, these methods have been generalized by synthesizing nonlinear n-ports having a prescribed multidimensional piecewise-linear driving-point function. Although most of the basic building blocks are grounded active networks, converter networks have been developed for transforming such grounded networks into floating networks having the same properties. By slight modifications of these converter networks, other useful conversion properties have also been developed.

*L. O. Chua and Robin L-P. Ying, "Finding all solutions of piecewise-linear equations," ERL Memo UCB/ERL M81/54, 23 July 1981.

More recently, this multidimensional piecewise-linear representation has led to the partial resolution of a heretofore unsolved conjecture first posed in 1978⁴. In a recent paper^{5,*} we have proved that every reciprocal n -port resistor represented by our n -dimensional piecewise-linear function is realizable by a nonlinear circuit containing only 2-terminal piecewise-linear i resistors and a reciprocal linear element, such as a $(p+q)$ -port transformer. This result thereby resolves one of the many fundamental questions raised in reference 6. In particular, we have proved the following:

Theorem 1. n -port Reciprocity Criteria

A piecewise-linear n -port described by

$$i_1 = a_1 + b_1 v_1 + \dots + b_{1n} v_n + \sum_{k=1}^{m_1} g_{1k} |\alpha_{1k_1} v_1 + \dots + \alpha_{1k_n} v_n - \beta_{1k}|$$

⋮

$$i_n = a_n + b_n v_1 + \dots + b_{nn} v_n + \sum_{k=1}^{m_n} g_{nk} |\alpha_{nk_1} v_1 + \dots + \alpha_{nk_n} v_n - \beta_{nk}|$$

is reciprocal if and only if

- a) $b_{ji} = b_{ij}$
- b) $m_j = m_i$
- c) $\alpha_{jk_1} = \alpha_{ik_1}, \quad k = 1, 2, \dots, m_j$

⋮

$$\alpha_{jk_n} = \alpha_{ik_n}, \quad k = 1, 2, \dots, m_j$$

$$\beta_{jk} = \beta_{ik}, \quad k = 1, 2, \dots, m_j$$

*The second author (David J. Curtin) was supported by the JSEP Contract F44620-71-C087.

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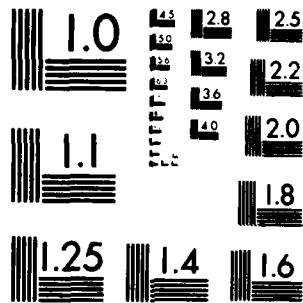
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Theorem 2. Reciprocal n-port Synthesis Criteria

A piecewise-linear n-port satisfying the above reciprocity criteria can be synthesized using only passive piecewise-linear 2-terminal resistors and a (p+q)-port transformer if and only if the set of algebraic conditions given in reference 5 is satisfied.

Both theorems 1 and 2 could not be proved without using our multidimensional piecewise-linear representation whose explicit analytical representation was crucial in constructing the piecewise-linear algebraic proof.

Recently, we have developed two approaches for realizing a (p+q)-port transformer using operational amplifiers.* Unlike iron-core transformers, our realization is valid from dc to a relatively high frequency, limited only by the op amp's frequency response.

2. Research Progress on Qualitative Nonlinear Network Analysis

Among the many important unsolved problems posed in the last major proposal concerning the foundation of nonlinear circuit theory, the following are some of the recent results published on this subject.

a. Implications of Capacitor-only Cutsets and Inductor-only Loops in Nonlinear Networks⁷

Let N be an autonomous dynamic nonlinear network. Let N_{RC} be the associated resistive subnetwork obtained by open circuiting all capacitors and short circuiting all inductors. We have proved the following results in reference 7.

- (1) Suppose that N_{RC} has only isolated operating points. Then N has only isolated equilibria, if and only if, there are no capacitor-only cutsets and inductor-only loops.
- (2) If the above condition is violated, then there are a continuum of equilibria even if the operating points are isolated.
- (3) Let M be the set of equilibria. Then each trajectory is constrained to lie on an affine submanifold M^* , which depends on the initial state, such that $M \cap M^*$ has only isolated points. Hence, each trajectory behaves as if it has only isolated equilibria. The space M^* , because of its nature, can be considered as the minimal dynamic space of the network.

The above results are of special relevance to the computer simulation of nonlinear electronic circuits⁸. The presence of inductor-only loops and capacitor-only cutsets could lead to serious numerical problems during integration. These issues have been the subject of several heated debates^{9,10} almost 20 years ago. The results presented in ⁷ provide a definitive and rigorous resolution of the fundamental issues raised in references 9 and 10.

*L. O. Chua, G. N. Lin and J. J. Lum, "The (p+q)-port transformer," ERL Memo UCB/ERL M81/41, 11 June 1981.

b. Dynamics of Josephson-junction Circuits¹¹

Although seemingly esoteric, the electromagnetic properties of Josephson junctions have been used in applications ranging from the measurement of minute computers with pico second switching times.

Although much has been published concerning Josephson-junction circuits, these articles are either quantum-mechanical analyses of the Josephson effect or sundry reports of experiments which reveal some very remarkable phenomena associated with circuits containing Josephson junctions. Those who have ventured to solve the differential equations of Josephson-junction circuits have necessarily restricted themselves to approximate methods, or the use of approximate analog models. The situation remains somewhat unsatisfactory from the circuit theorist's point of view, as only a very limited insight is available into the general circuit behavior of the devices.

Our research on Josephson-junction circuits was concerned mainly with developing a unified qualitative theory of the phenomena associated with Josephson-junction circuits. Some recent progress has been reported¹¹. In particular, the features of the d.c. I-V characteristic of a Josephson junction have been explained rigorously in terms of the flows on a cylindrical phase space. The junction phase difference ϕ attains an equilibrium point in the supercurrent regime, and acts like a current-controlled oscillator in the finite voltage regime. The hysteresis in these characteristics is due to the coexistence of an equilibrium point and a periodic solution.

For the a.c. excited Josephson junction, the dynamics are described for a simpler circuit model as trajectories on the surface of a torus. Using the concept of a turning point to define the various possibilities of periodic flows on the torus,, the character of harmonic and subharmonic oscillatory waveform has been derived. Furthermore, the existence of almost periodic waveforms has been established. The presence of constant-voltage steps is related to the structural stability of the turning point, which roughly means that the character of a periodic oscillation is not affected by small enough perturbations in the excitation. An algorithm is given in reference 11 to numerically determine the heights of these constant voltage steps.

A precise interpretation is also given in reference 11 showing how an a.c. excited junction is subject to synchronization phenomena, and that the step height is merely the entrainment range, or locking range, of each synchronization event. It is also shown how synchronization, in general, can be geometrically interpreted as closed trajectories on an integral manifold which can be smoothly transformed into an n-dimensional "torus."

c. Theory of Symmetry in Nonlinear Circuits ^{12,13}

Simple group-theoretic concepts have been used successfully in references 12 and 13 to develop a rigorous and comprehensive theory of symmetry for nonlinear elements and circuits. This theory does not rely on geometrical arguments or other ad hoc techniques normally invoked in such studies. This theory also unifies all forms of symmetry, including

rotation, reflection and complementary symmetry into a single framework. It also includes all known nonlinear symmetry principles as special cases. Moreover, a general method for identifying all symmetry characteristics possessed by a nonlinear multiterminal element or circuit has been obtained. Some of the results that have been obtained concerning symmetry in a nonlinear element are:

(1) Several algorithms for synthesizing a nonlinear multiport or multiterminal element having any prescribed form of symmetry have been derived. In particular, various examples have been used to illustrate how these algorithms can be used to derive well-known symmetrical nonlinear circuit modules such as push-pull amplifiers, complementary-symmetric amplifiers, rectifiers, modulators, etc.

(2) A reduction algorithm has been developed which allows a complicated symmetric element to be analyzed by a much simpler reduced element.

(3) A general principle has been derived for applying symmetry to achieve frequency separation in nonlinear communication circuits where the even harmonic components are separated from the odd harmonic components.

d. Passivity in Dynamic Nonlinear n-ports

In this research* we have succeeded in stating rigorously the energy-based concepts which are fundamental to nonlinear network theory, passivity and losslessness, and clarifying the way they enter the input-output and the state-space versions of the subject. We examined the conflicting definitions of passivity which exist in the literature and demonstrated the contradictions between them with several examples. We proposed a particular definition of passivity which avoids these contradictions by eliminating the dependency on a state of "zero stored energy," and we showed that it has the appropriate properties of representation independence and closure. We applied it to several specific classes of n-ports and derived equivalent passivity criteria. The exact conditions are given under which this definition is equivalent to one based on a internal energy function, and we used the concept of an internal energy function to provide a canonical network realization for a class of passive systems.

e. Geometric Properties of Dynamic Nonlinear Networks

In this research,** we have derived several basic results on

*J. Wyatt, Jr., L.O. Chua, J. W. Gannett, I. C. Goknar and D. N. Green, "Energy concepts in the state-space theory of nonlinear n-ports: Part I - Passivity," IEEE Trans. Circuits and Systems, Vol. CAS-28, Jan. 1981, pp. 48-61.

**T. Matsumoto, L. O. Chua, H. Kawakami and S. Ichiraku, "Geometric properties of dynamic nonlinear networks: transversality, local solvability and eventual passivity," IEEE Trans. Circuits and Systems, Vol. CAS-28, May 1981, pp. 406-428.

dynamic nonlinear networks from a geometric point of view. One of the main advantages of a geometric approach is that it is coordinate-free, i.e., results obtained by a geometric method do not depend on the particular choices of a tree, a loop matrix, state variables, etc. Therefore, the method is suitable for studying intrinsic properties of networks.

We have shown that transversality of resistor constitutive relations and Kirchhoff space is a sufficient condition for the configuration space to be a submanifold. Our main result states that a network is locally solvable, i.e., the dynamics of a network is well defined in the sense of Definition 3, if and only if, capacitor charges and inductor fluxes serve as a local coordinate system for the configuration space. In other words, if all the variables in a network are determined as functions of capacitor charges and inductor fluxes, at least locally, then the dynamics is well defined. Conversely, if the dynamics is well defined, then all the variables in a network are determined as functions of capacitor charges and inductor fluxes. Because of its coordinate-free property, our main result also says that if the dynamics is well defined in terms of some coordinate system, then it must be well defined in terms of capacitor charges and inductor fluxes. Conversely, if the dynamics is not well defined in terms of capacitor charges and inductor fluxes, then there is no choice of variables in terms of which the dynamics is well defined in the sense of Definition 3. This shows that capacitor charges and inductor fluxes are the fundamental quantities in describing the dynamics of networks. Perturbation results are given which guarantee transversality and local solvability. Finally, several other perturbation results are given which guarantee eventual strict passivity of dynamic nonlinear networks. They explain why the voltage and current waveforms of almost every network of practical importance are eventually uniformly bounded.

3. Research Progress on Circuit Layout and Routing

During the past year a major effort has been made on the routing aspect of circuit layout. The work includes three distinct problems, namely:¹³

- (i) Global wiring and the Steiner problem,
- (ii) Generalized channel routing, and
- (iii) A new approach to 2-layer routing.

(i) The problem of global wiring is of theoretical interest and has significant practical value. It represents an important step in automatic layout of master-slice and building-block chips. We have developed a heuristic algorithm to solve the minimum Steiner tree problem with rectilinear distance. This will be a key part of the general program which we are developing on global wiring.

(ii) We have extended our early work on channel routing to include channels which have cyclic constraints¹⁶. A new program is being developed based on a totally different approach on 2-layer routing. The preliminary result is encouraging. In special cases the resulting

channel width could be smaller than the traditional lower bound of maximum density.

(iii) In the traditional approach to automatic routing of 2-layer printed circuit board, a unidirectional method is used. This depends on the strategy of using one layer for horizontal connection and the other for vertical connection. The interconnection between layers is made through via holes. In a new approach, we have demonstrated that it is possible to save about half of the vias required in the traditional approach¹⁴. On the other hand, it is difficult to control the congestion between pins and vias. However, by using a different via assignment procedure, we can offer more flexibility in routing¹⁵.

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Significant Accomplishments

The major results have been summarized under Sections 1, 2d and 2 e.

Proposed Research Program

Although much progress has been obtained since our last major JSEP

proposal entitled "Large-scale and nonlinear circuits study," many of the problems proposed in that proposal have not yet been pursued. Others are still under continuing research*. We proposed therefore to continue our research along the lines described in our last major proposal. The following is a summary of the proposed research program:

1. Piecewise-linear analysis of general nonlinear networks. While piecewise-linear analysis has been proven to be a powerful method for analyzing large, nonlinear resistive networks, its application to circuits with capacitors and inductors has not been found useful. Preliminary studies have indicated that a source of difficulty lies in the noncommutative property of matrix multiplication. However, we believe that techniques can be developed to deal with special classes of nonlinear dynamic systems. In particular, the concept of decomposing a general RLC nonlinear circuit into three subnetworks should be explored. Also, the problem of matching boundary conditions at discrete time needs to be investigated.

2. Spline approximation. While the piecewise-linear approximation has the distinct advantage of reducing a nonlinear problem into a linear one over a given region, thus greatly simplifying the computation, it does not yield the desired accuracy for certain problems. To improve accuracy, spline approximation can be used. On the other hand, with spline functions, one needs to solve nonlinear equations over each region. The technique developed in Katzenelson's algorithm which involves the crossing of simple boundaries cannot be used directly. We propose to study the use of spline functions in solving nonlinear resistive network problems. It is possible that a combined piecewise-linear and spline function method can be devised.

3. Simplicial interpolation. In our most recent work on piecewise-linear analysis, we introduced the method of simplicial interpolation for approximating an n-valued function. A key first step is to select an n-dimensional rectangle in a bounded set in which the solutions lie. The method of simplicial subdivision provides a systematic way to tessellate an n-dimensional rectangle into simplices. With this, the necessary computation in piecewise-linear analysis which deals with boundary crossing becomes greatly simplified. However, further work is needed, both in determining the bounded set and in choosing a suitable initial grid. The present algorithm uses simplices of the same size until an approximate solution is found. More work is needed in increasing the efficiency of computation.

The method of simplicial approximation has also been found useful in tolerance analysis of large scale circuits^{1,2}. The method proposed by Director and Hachtel locates and approximates the boundary of the feasible region of a design space with a simplex of boundary hyperplanes. It gives solution to the tolerance assignment problem, and thus

*That proposal was written from a long-range planning point of view and included many more basic research problems than we were prepared to pursue. This was done in order to provide a better perspective on the relationship between the various proposed topics of research.

is capable of evaluating a given design. The computation steps required are substantially less than those of the Monte Carlo method.

It is clear that simplicial approximation is a powerful tool for studying many types of large-scale circuit and system problems. The unique feature of the method lies in its computational elegance and simplicity. Yet, for each type of application, different techniques must be developed. We propose to generalize its applications and study many of its salient features.

4. Diakoptic analysis of dynamic nonlinear networks. Our recent work on large-scale networks has shown that there exists a one-to-one correspondence which equates any form of diakoptic or codiakoptic analysis to a special case of generalized hybrid analysis. This result unifies both diakoptic and codiakoptic analysis into a simple circuit-theoretic concept independent of any linearity assumption. In other words, this concept should be applicable also for nonlinear and dynamic networks. To obtain this generalization, we propose to develop algorithms for decomposing a large system of nonlinear ordinary differential equations -- such as those associated with nonlinear LSI circuits -- into several subsystems coupled to each other in a form analogous to the decomposition of a generalized hybrid matrix into a bordered block-diagonal, or a bordered block triangular form. This decomposition step is not only convenient, but is in fact essential when a very large system of state equations has to be solved. Indeed, even using the most advanced sparse matrix technique, the computer cannot handle large systems of nonlinear differential equations effectively.

Various decomposition methods will be exploited and the relative computational efficiencies compared against each other. Since each method decomposes the solution process into several stages, each involving a relatively small system of equations, it can be implemented via the so-called "small-computer approach;" namely, one can either apply the overlay techniques to "stack" the decomposed solution states, or apply parallel computation techniques to speed up the solution process.

We also propose to develop methods for investigating the qualitative behaviors of large-scale nonlinear dynamic networks by analyzing the behaviors of the decomposed subnetworks. For example, if each subnetwork is asymptotically stable, or completely stable, can we conclude that the same property holds in the original network? Our preliminary study on this important question shows that the qualitative properties of the decomposed dynamic subnetworks are not generally preserved in the original network. However, we were able to prove that many properties are preserved if additional assumptions of a topological nature are imposed³. We propose, therefore, to apply the recent techniques developed^{4,5} to derive corresponding results for large-scale dynamic nonlinear networks.

5. Qualitative analysis of nonlinear communication circuits. With the exception of amplifiers and active filters where nonlinearities are undesirable, most communication circuits such as oscillators, mixers, and frequency converters are inherently nonlinear in the sense that their operation depends crucially upon the presence of at least one

nonlinear element⁶. In fact, even some "linear" input-output systems such as the parametric amplifier must be designed around a nonlinear element. Although nonlinear circuits can now be analyzed with the help of computer simulation programs⁷, the resulting information is often inadequate from the designer's point of view. Indeed, there are many questions of a non-numerical nature which are more vital to the proper operation of the system.

For example, depending on the initial condition, it is well-known that nonlinear circuits can exhibit several distinct modes of operation. In fact, one perennial problem that confronts designers of parametric amplifiers and frequency converters is the sudden burst of unwanted subharmonic oscillations. Unfortunately, unless the designer knows what initial conditions would give rise to such anomalous operations, the existence of spurious operating modes may not be detected by computer simulation. Such information could be obtained, however, by carrying out a qualitative analysis of the associated system of nonlinear differential equations⁸.

There are many other important questions of a qualitative nature which the circuit designer must answer in order to arrive at a good design. Some of these questions are: Will the circuit be stable or will it oscillate (except in the case of an oscillator)? If the circuit is stable, what are the different modes of dynamic operation? Will there be a unique steady state response? If so, how fast does the transient decay to the steady state? What are the effects of noise and parasitic elements on the operation of the circuit? In the case of amplifiers, what are the dominant distortion terms and how can they be calculated efficiently? In the case of frequency converters, how are the frequency and power related to each other? Is it possible to derive a generalized form of frequency-power relationships analogous to either the Manley-Rowe or Page-Pantell type for nonlinear devices modeled by more than one type of circuit elements? How can conversion efficiency be improved? How do we design an optimally matched nonlinear circuit?

While answers to some of these questions have been given for specific circuits containing diodes and transistors^{9,10}, they are generally rather ad hoc in nature and depend heavily upon the network topology and the devices being used. Since future communication circuits are certain to contain such modern microwave devices as Gunn diodes, IMPATT's, GaAs FET's, etc.¹¹, it is essential that more unified methods be developed. We propose therefore to continue our research in this area with the ultimate objective of developing such a unified theory.

6. Piecewise-linear algebra. Research on piecewise-linear analysis over the past decade has been concerned mostly with the development of efficient computer algorithms and the investigation of the existence and uniqueness of solutions. Very little attention has yet been given to the algebraic operations on equations involving piecewise-linear functions because such functions have so far been represented as a collection of systems of linear equations, each holding over a prescribed region in space. Our recent discovery of an explicit analytical formula for representing piecewise-linear functions of one

variable¹² shows that the class of all networks containing piecewise-linear two-terminal elements can be described using only two basic nonlinear building blocks; namely, the "absolute-value function" $y = |x|$, and the "sign function" $y = \text{sgn } x$. Using this representation, the equilibrium equations of networks containing two-terminal piecewise-linear elements can now be written in analytic form. This is analogous to writing equilibrium equations for linear networks in matrix form. The analysis of linear networks is an easy task, mainly because of the availability of "matrix algebra" as a tool of analysis. Unfortunately, no corresponding tools are available for analyzing nonlinear networks because of the infinite variety of nonlinearities that must be considered. However, by restricting the class of nonlinearities to include only the "absolute value function" and the "sign function," it is quite hopeful that such an algebra would automatically allow any piecewise-linear function of one variable* and we would have in fact developed an algebra for analyzing networks containing piecewise-linear elements.

The development of a "piecewise-linear algebra" would make it possible to carry out a symbolic analysis of networks containing piecewise-linear elements. In particular, various nonlinear network functions of practical interest -- such as the driving-point and transfer characteristics -- can be derived in symbolic form. Another application of the piecewise-linear algebra would be to derive design equations where the important design parameters are preserved in symbolic form. This in turn would allow a sensitivity analysis to be made via algebraic operations alone.

To summarize, we propose to apply our newly discovered analytical representation to develop a piecewise-linear algebra for analyzing and designing circuits containing piecewise-linear elements.

7. Computer-aided circuit analysis, design and layout. Recent advances in microelectronics have created an urgent need of new approaches to circuit analysis, design and layout. This research project is concerned with two problem areas, namely: (a) piecewise-linear circuit analysis and simulation, and (b) theoretical studies of layout for integrated circuits and printed circuit boards.

(a) Piecewise-linear circuit analysis and simulation

The idea of piecewise-linear analysis first introduced by Katzenelson in 1965 has been fully developed by us, and a complete theory of piecewise-linear analysis is now available. The theory has broad applications in nonlinear circuits and systems. The method has advantages over conventional methods, for example, in calculating driving-point or transfer characteristics of circuits with negative slopes. Yet circuit simulation based on the piecewise-linear method has not been widely used. There are two main reasons, namely: the problem of corner crossing, and the lack of study of convergence.

*We have good reason to believe that the same technique could be generalized to allow piecewise-linear functions of many variables.

Recently, two notable approaches emerge which will greatly enhance the power of the piecewise-linear method.

The first which is developed by us is the use of simplicial approximation. With simplicial approximation we can simplify the task of computing the solution curve. There remain two problems to be investigated, namely: the corner-crossing problem and the problem of choosing the size of the initial complex. Both will affect the convergence of the method.

The second approach is to use ideal diodes and linear resistors only in modeling. This has the advantage that transition between regions can be handled by linear programming. Furthermore, the ideal diode model fits naturally to timing, logic and function simulation. Much more work needs to be done with this approach. For example, the problem of sensitivity and tolerance has never been attacked. Also, the problem of fault diagnosis in ideal diode circuits is worth studying because it is simpler than fault diagnosis of analog circuits and could possibly take advantage of the techniques well-known in digital circuits.

(b) Layout study

With the advent of VLSI, the problem of layout has reached a new dimension. We believe it is highly important to develop theoretical concepts on what could be done. Recent literature is by and large restricted to program development and almost void of analytical results. Many problems need to be investigated.

The problem of placement is perhaps the most important and difficult. Existing work deals with either placement of uniform modules or small analog circuits. Nowadays, in custom LSI, modules of various shapes and sizes with thousands of interconnections need to be considered. Thus, net list alone, which gives information on connection, is not enough for optimum placement. It is necessary to consider both the geometries and the topological specifications. We believe that graph theoretical concepts are essential in algorithm development.

A related problem is to predict the size of a chip from the geometric and topological information. As chips become more dense, the percentage of space needed for routing will further increase. The task of chip planning is fundamental to IC design. Of course efficient routing is implied in chip planning. Although methods of channel routing and global routing are available, no optimum results exist. In this connection, we have recently developed highly efficient channel routing algorithms based on graph theoretical considerations. More such studies will be carried out, for example, in channel routing with more than two layers.

Finally there is a need to develop circuit simulation programs directly from layout information. This involves the modeling of devices as well as parasitic elements.

Interaction With Other Work Units

We anticipate interacting with the CAD efforts of Professors Polak and Sangiovanni-Vincentelli, as well as the large-scale system research of Professors C. A. Desoer, P.P. Varaiya, R. W. Brodersen et al. (Work units ISS-81-2 and SSD-81-4 respectively).

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Electronics Research Laboratory

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Work Unit No.: ISS-82-2

Last Year's No.(s): ISS-81-2

Title: Control of Large Systems

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Scientific Objective

The overall long term objective is to design control structures for unknown systems subject to random disturbances. The class of structures being investigated is the so-called "adaptive feedback control" laws, the unknown system is any countable state Markov chain whose unknown transition probabilities are parameterized. Also to be studied is the practically important case where the "real" system does not belong to the class of a priori selected models. In conjunction with this work, deterministic system design methods and evaluations are also investigated.

State of the Art

Over the past twenty-five years engineers have invented a variety of procedures for designing control strategies. The sophistication of these strategies has grown with the increase in the use of computers which enables the implementation of complicated strategies in real time (feedback control). But all these procedures rest on the assumption that the information available about the system and the calculation of the choice of control which is based on this information is centralized, that is it takes place in a single system.

As engineers began to consider the control of large systems* (e.g., power systems, communication networks) in a scientific manner, it became clear that "classical" procedures of design are inapplicable to the problem of Combinatorial Complexity. As the number of variables describing the system increases, the amount of computation necessary to apply classical control strategies grows even faster, soon exhausting the capability of existing and foreseeable computing capability. It was soon recognized that a way of dealing with this complexity is to insist on decentralized control strategies¹⁻⁴. After this recognition, research has proceeded in three directions. First, there has been the attempt to derive design principles applicable to a fairly general class of decentralized controllers^{5,6}. But this attempt was soon frustrated by a new difficulty, Informational Complexity^{**}. As soon as information and control is decentralized, the information available and the effectiveness of the decision taken by each controller depend upon the decisions taken earlier by other controllers. This "simultaneity" reproduces the Combinatorial Complexity at another level and renders inapplicable existing techniques of controller design. The difficulties created by Informational Complexity are not well understood. On the one

*Systematic attention to the control of large systems began less than ten years ago. An indication of this is given by the fact that the IEEE Control Systems Society established its Technical Committee on Large Scale Systems in 1969, its first editorial on large systems appeared in 1974, and its first Special Issue on Large Systems in April 1978.

**We are indebted to Professor Y. C. Ho (personal communication) for his conceptualization of these two kinds of complexity.

hand we have several counterexamples of decentralized control problems which appear quite innocent, but whose optimal strategies are extremely complex^{7,8,16}. On the other hand, we now know a (small) class of decentralized information structures for which optimal control strategies do have a simple structure⁴.

The second direction of research has led to the search of optimum decentralized controllers for what have been called quasi-static control problems⁹. For these problems optimum controllers can have a simpler structure since only "steady state" behavior is of interest. Some very interesting solutions have already been proposed for the control of network flows¹⁰ and for routing messages in a communication network¹¹.

Whereas the second direction described above seeks to reduce complexity by simplifying the control task (attention to steady state and ignoring transient behavior), the third direction reduces complexity by restricting a priori the structure of the class of decentralized controllers. In designing fixed structure controllers which guarantee adequate response against random disturbances, the attempts to date have been ad hoc¹²⁻¹⁵. It seems clear that considerable advance can be made if fixed structure decentralized controllers are investigated more systematically. This prediction is bolstered by the results recently obtained in the study of decentralized linear feedback controllers which guarantee adequate response against "deterministic but unknown" disturbances.

With the goal of designing robust controllers for large scale systems, the following approaches are relevant. First there is a very considerable literature on the stability of interconnected systems based on the Lyapunov method. In terms of generality of the results and of technical sophistication, the paper of Rasmussen and Michel deserves special mention¹⁷. Second, the problem can be approached from the input-output point of view: given the input-output properties of the subsystem and the topology of the interconnection, describe the I/O properties of the overall system. Under the joint sponsorship of NSF and JSEP we conducted a thorough investigation of this problem¹⁸. We refer the reader to its 46 item reference list. Recently we produced an improved formulation of the problem which led us to necessary and sufficient conditions for stability, even for the nonlinear case. The goal of this research is to study the input-output properties of the overall system. The advantage of the approach, namely graphical decomposition, is that it applies equally to nonlinear time-varying just as well as linear time-invariant systems, either lumped or distributed. The graphical decomposition technique operates as follows: the digraph of the interconnected subsystem is decomposed into an acyclic interconnection of strongly connected components and then a minimal essential set is extracted to further simplify the analysis of the strongly connected components.

On the decentralized control of large systems, especially as it relates to tracking and disturbance rejection, the work of Davison^{19,20} deserves special mention. We used it as well as graphical decomposition techniques to investigate the eigenvalue assignment and stabilization

problem of linear time-invariant interconnected systems²¹; one main result is that we can achieve eigenvalue assignment provided we operate at the column subsystem level, whereas if we restrict ourselves to summation node level, examples show that eigenvalue assignment cannot be achieved in general, whereas we prove that we can achieve stabilization²¹.

On the more specific topic of tracking and disturbance rejection, the considerable literature and several approaches used are reviewed in reference 22. Furthermore, the principal results are given a streamlined self-contained derivation in reference 23. Unfortunately, all this literature considers only linear, usually lumped systems and discusses robustness of the servocompensators only within that class²⁴. The effect of nonlinear plant perturbation on optimal control design has recently been examined in references 25,26; in the broader aspect of I/O stability in references 27-29.

Only one recent report treats the tracking problem for nonlinear systems³⁰.

Adaptive control strategies are increasingly being suggested as an appropriate solution to the situation where the system to be controlled is not known and is subject to random disturbances. Adaptive control is a compromise between two extreme alternatives. The first: assume the unknown system is equal to a "nominal" system, may give a performance which is unacceptably degraded; the second: formulate the problem as a Bayesian decision problem and solve it by Dynamic Programming, while formally optimal, it cannot be "solved" except in the most trivial instances.

In adaptive control, one identifies the unknown system using previous data; and then uses the control assuming the current estimate of the unknown system to be the true system. As time progresses, and more data is collected, the uncertainty regarding the system declines and the performance improves. The crucial question is how fast this improvement in the knowledge and performance of the system occurs. Previous research has been primarily focused on linear systems.

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Progress and Relevant Publications Since Last Major Proposal

A. Under Combined Sponsorship

1. Control of Markov Chain Models

We have completed the first phase of the research. Our work (and of others in the field) is summarized in [a]. This research dealt with the control of Markov chains when the transition probabilities are not known a priori. Then the function of control action is to simultaneously learn the system parameters and to guide the system in a desired fashion. The strategy adopted to do this is adaptive control. Here at each time instant the past observations are used for parameter estimation and the next control action assumes that the estimate is true.

Two ideas for estimation have appeared. The original one is to use the maximum likelihood estimate (MLE). Kumar has modified this by multiplying the likelihood function by a term that corresponds to the reward. The resulting estimates have some desirable properties not enjoyed by the MLE.

Convergence of estimates is guaranteed when the parameter set is finite but not when it is infinite. Nevertheless, Kumar's modified MLE produces a control which is optimal. The problem of finding conditions to ensure parameter convergence seems rather difficult.

2. Design of Deterministic Control Systems

Fundamental studies in nonlinear feedback systems have been completed: a general theory of multi-input multi-output nonlinear feedback systems has been completed and published^[h]. It gives a complete generalization of the theory that H. S. Black presented for the linear time-invariant single-input single-output feedback system. In addition, it gives a completely general demonstration that the linearized inverse return difference is the quantity that controls the degree of desensitization to plant and/or output disturbances. It is also shown to play a key role in linearizing the I/O map of the closed-loop system.

The streamlining of the theory of the generalized Nyquist criterion and its generalization to the distributed case has been published^[i]. We hear that the method has been programmed and is being used at TRW in Los Angeles. The features of our generalized Nyquist criterion is that (a) it applies to the distributed case, and (b) it does not require any reference to Riemann surfaces, branch cuts, etc. that previous derivations required.

An interesting approach to the study of linear feedback systems due to Zames has been adapted to the problem of designing multivariable feedback systems with stable plants. This design method is revolutionary in that (a) it is based on the global parameterization of the four transfer functions pertaining to the problem, and (b) the stability of the design is easily checked without having recourse to such things as Nyquist diagrams etc. The design algorithm allows complete freedom - modulos, of course, the C_+ - zeros of the plant - in the choice of I/O map: therefore we can diagonalize the I/O map, assign zeros independently to each channel, assign poles independently to each channel and achieve tracking requirements. The simplest version of the algorithm was presented at the 1980 JACC^[j], an extension of it will be presented at the 1980 CDC^[k]. The first paper describing the algorithm has been accepted by the IEEE Trans. on Automatic Control. We are working out several extensions: one of our goals is to obtain a completely algebraic

theory of design^[1]..

Many studies devoted to the effect of the plant perturbation on the stability of the system require that the perturbation be represented by stable operators. This is totally unrealistic in the case of an unstable plant: indeed, any perturbation in an unstable pole requires an unstable multiplicative perturbation^[k,1].

B. Under NSF Exclusive Sponsorship

In NSF grant ENG78-09032 Desoer is investigating control problems for discrete-time^[m] and continuous time^[n] systems. Also, in^[o], Desoer et al. demonstrated that the design algorithm developed under JSEP sponsorship did not impose unnecessary constraints on the choice of the I/O map. With a master's student, we are tying the design algorithm technique with Professor Polak's inequality constraint approach to design. Simple examples show that the method works and gives a rational technique for selecting parameters^[p].

C. Significant Accomplishments

The spread of computer-assisted control has increased the possibility of implementing adaptive controllers which "tune" the control inputs to automatically detected changes in operating conditions. Considerably more work needs to be done, and this will take several years, before adaptive controllers can be implemented on a routine basis.

Work on statistical identification has shown us that it is possible to design experiments to identify an unknown system, and engineers have developed many methods for controlling a known system. The aim of adaptive control is to carry out both tasks - identification and control - concurrently. Our investigations, and the work of others, have proved that, in principle and under precisely stated conditions, this is indeed possible. Others have shown that adaptive controllers will operate satisfactorily for linear systems of the form:

$$\sum a_i y_{t-i} = \sum b_i u_{t-i} + \sum c_i w_{t-i}$$

where y_t , u_t , w_t are the output, input and white noise and the a_i , b_i , c_i are unknown parameters. Our work has resulted in conditions for the satisfactory control of systems of the form:

$$x_{t+1} = f(x_t, w_t, u_t, \theta)$$

where x_t is a discrete state, and θ is the unknown parameter.

A very exciting development in control system design occurred: by adapting a global parameterization of Zames, we have developed an algorithmic method of design that guarantees system stability, that guarantees a strictly proper controller and that can accomplish the following: (a) decouple the system, (b) assign the poles individually in each channel, (c) except for the C_+ -zero imposed by the plant, assign the zeros in each channel, and (d) achieve tracking requirements. It is apparent that the technique is very general and applies to any algebraic system

of a certain kind (e.g., continuous-time or discrete-time, lumped or distributed). The method lends itself naturally to interactive computer-aided design methodologies.

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Proposed Research Program

The general outline of the research program in large scale systems

is a long term program in the course of carrying it through: there are certain innovations that have to be pursued because it is intuitively clear that they will have important — though unknown at present — effects on the Large Scale Systems research program

Over the coming period we plan to develop our work in adaptive control along the following directions:

The research done so far uses a so-called "passive" learning in which the fact that the system parameters are unknown does not affect the control used. Such a strategy may perform poorly for short horizon problems.

Recently some fundamental breakthroughs have been achieved for the classical multi-armed bandit problem (see [b,c,d] and the references there). The dynamic structure in bandit problems is simpler than the general Markov structures we have investigated; however, bandit problems consider discounted cost functions, i.e., they include "transient" behavior, while our problems only considered "steady state" behavior.

For determinate systems the proposed research will attempt to extend the results on the bandit problems to more complex dynamics. The most promising extension seems to be to consider a set of bandits operating in a common Markovian environment.

- (1) We will vigorously pursue the extension of the new design algorithm: we believe that we should be able to give a completely algebraic theory of design which would be applicable to square or rectangular, discrete-time or continuous-time, lumped or distributed plants.
- (2) We will critically reexamine Youla's parameterization to see whether some dramatic simplification as occurred in the stable plant case cannot be caused to occur for the unstable plant case. If not, we propose to investigate the best stabilization method.
- (3) We will develop extensions of the technique to large scale systems.

Interaction with Other Units

We shall continue to interact with the research project of L. O. Chua and E. S. Kuh on nonlinear circuits and with E. Polak on computer optimization of electronic circuits.

University of California, Berkeley

Electronics Research Laboratory

Joint Services Electronics Program

September 30, 1981

Work Unit No.: ISS-82-3

Last Year's No.(s): ISS-81-3

Title: Computer Optimization of Electronic Circuits

Senior Principal Investigator(s): A. Sangiovanni-
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2-2644

Scientific Objective

This project is a continuation of Project ISS-82-3, Computer Optimization of Electronic Circuits. Our chief objective remains the development of an interactive, optimization-based, computer-aided design methodology for the design of electronic circuits. To this end, we propose to continue developing specialized, dovetailing, single and multi-objective optimization algorithms, circuit simulation techniques and device models. In addition, since the development of progressively more complex systems makes sense only if these systems can be maintained, we propose to perform research on system diagnosability and fault analysis.

The optimization algorithms to be developed must be capable of solving complex, nondifferentiable, semi-infinite optimization and trade-off problems which arise in electronic circuit design when tolerances, trimming, and distributed constraints are taken into account. Our simulation procedures must be capable of producing not only circuit responses, but also the derivatives of these responses with respect to design parameters. In addition, they must have special variable precision features which result in a reduction of computing time at low precision, so that an optimization algorithm can call such a procedure with low precision when far from a solution and increase precision adaptively, as a solution is approached. The effect of such variable precision computation is to considerably reduce computing times. Since production tolerances can be imposed on only a very small number of device parameters, and since the optimization algorithms become extremely inefficient when tolerances on a large number of parameters are specified, device models must be developed in terms of production parameters by making use of the fact that the variation of many circuit parameters can be expressed in terms of variations of production parameters.

Finally, our theoretical work will be implemented and experimentally evaluated in an interactive-computer aided design facility which we are developing.

State of the Art

Optimization-based computer-aided design is certainly not a new phenomenon, see for example [B9,B11,B13,B15,B20,C1,K1,K2,P7,H16]. However, until quite recently, its use was severely limited by the fact that the available optimization algorithms were not able to solve design problems with tolerances, trimming and distributed constraints, such as those imposed on frequency or transient responses [B20]. The reason for this is that such a design problem frequently assumes the form

$$\min f(x) \mid g^i(x) \leq 0, i = 1, 2, \dots, I; \max_{w \in W} h^j(x, w) \leq 0, j = 1, 2, \dots, J;$$

$$\max_{e \in A} \max_{s \in S} \min_{t \in T} \max_{k \in K} z^k(x, e, s, t) < 0 \quad (1)$$

where $g^i(\cdot)$ represents simple constraints on the nominal design vector x , $h^j(\cdot, \cdot)$ represents nominal frequency (or time) dependent constraints

on impedances or gains, etc., and z represents the requirement that performance be maintained in the presence of production errors e which can be counteracted by adjusting the trimming parameters t . The variable s may represent time or frequency or temperature, etc. The above problem is easily recognized as a non-differentiable, semi-infinite optimization problem, i.e., about as difficult an optimization problem as one cares to think of.

Although there is a fairly large literature on algorithms for various classes of semi-infinite and nondifferentiable optimization problems, see e.g., [B25,B26,B27,D8,D9,G6,G7,G8,H12,M10,P14,P16,P17a,H1,T1], we find that many of these algorithms are either conceptual (i.e., involve operations that one is not able to perform) or address themselves to very restrictive classes of problems, such as those with one-dimensionally convex constraint sets [B9,B11,B13,B15]. As far as general purpose, implementable algorithms are concerned, there appear to be only three [P14,G6,T1] which solve the simpler case of (1) when there are no tolerance and trimming constraints present, two [G6,P4] which allow for tolerances and only one [P5] which solves (1) in its complete generality. All of these three algorithms were co-authored by E. Polak.

In addition to the difficulties mentioned above, the use of optimization techniques in electronic circuit design was, and still is, severely handicapped by the fact that existing simulation codes, e.g. the ones described in [K1,J6,Z2], which must be called for function and derivative evaluation, have inadequate provisions for derivative calculations. For example, if we consider a sample of the best known computer aided analysis programs, such as ASTAP [A6], CIRCUS [D7], ECAP [E2], NET 2 [M7], SCEPTRE [B61], SUPERSCEPTRE [S12], SPICE 2 [N3] and BELAC [G12], we find, quite typically, that ASTAP computes no sensitivities, SPICE 2 computes only small-signal sensitivities, and none of them compute temperature sensitivity. We are now beginning to develop an effort to extend these programs so that required derivatives will also be computed. In addition to the simulation programs mentioned above, programs based on tearing algorithms [B28,C9,H5,H6,K8,M14,R1,S3-S8,S10,S11,W5], and on model approximation and decoupling [C6,F1] are also being considered for extension since they are more efficient in large-system applications.

As specialized optimization algorithms began to be developed for electronic circuit design, such as [P4,P5], it became obvious that existing device models were completely incompatible with the need of keeping the total number of toleranced variables small. Quite recently R. G. Meyer was able to show that more suitable models can be developed, because many of the important variables are correlated, and that their behavior can be expressed in terms of a reasonably small number of variables the tolerances on which can be controlled in the production process, such as sheet thickness, resistivity, device scaling factors, epitaxial doping, etc.

As far as fault diagnosis is concerned, we find theoretical results for the diagnosability of linear circuits and systems [B1,B3,B4,E3,L1,N1,R2,R3,S1,S2,S11,T1,T4-T6]. Some preliminary results for the diagnosability of memoryless nonlinear circuits and systems were co-authored by A. Sangiovanni Vincentelli [S12]. However, there appear

to be no diagnosability results for dynamic nonlinear circuits and systems.

Progress and Publications Since Last Major Proposal.

A. Under JSEP

1. Existing semi-infinite optimization algorithms used in engineering design are very reliable. However, since they are only first order methods, they are rather slow. Now, engineering design via optimization involves a great deal of time-consuming simulation and hence, in conjunction with first order methods, can be quite expensive in computer time. Obviously, there is a great need for faster methods. Professor E. Polak, in collaboration with Professor D. Q. Mayne of Imperial College, London, and Andre Tits, a graduate student, have made a considerable amount of progress in devising superlinearly converging algorithms for solving nonlinear semi-infinite optimization problems encountered in engineering design. Their work is reported in the following three papers.

D. Q. Mayne and E. Polak, "A quadratically convergent algorithm for solving infinite dimensional inequalities," University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M80/11, 1980. To appear in J. of Appl. Math. and Optimization.

E. Polak and A. Tits, "A recursive quadratic programming algorithm for semi-infinite optimization problems," International Symposium on Semi-infinite Programming, University of Texas, Austin, September 8-10, 1981.

E. Polak and A. Tits, "A quadratically convergent recursive linear programming algorithm for constrained nonlinear programming problems," University of California, Berkeley, Electronics Research Laboratory Memo UCB/ERL M80/50, 1980; 10th IFIP Conference on System Modeling and Optimization, New York August 31-September 4, 1981.

2. We have made a great deal of progress in constructing an interactive computing system for optimization-based computer-aided-design. Our present package, DELIGHT, offers an extremely high level language for very rapid and easy optimization program writing; extreme modularity, which permits very simple assembly of algorithms and problems from blocks; easy interface to simulation and system definition packages such as SPICE; various interrupt and restart features; powerful graphics; etc. Our progress to date on this system is described in:

W. Nye, E. Polak, A. Sangiovanni-Vincentelli and A. Tits, "DELIGHT: an optimization-based computer-aided-design system," University of California, Berkeley, Electronics Research Laboratory Memo UCB/ERL M81/19, 1981; Proc. IEEE Int. Symp. on Circuits and Systems, Chicago, Ill, April 24-27, 1981.

3. In our earlier work on design centering, tolerancing and tuning problems, we discovered that these problems are inherently nondifferentiable. An examination of the literature showed that there was very

little available by way of nondifferentiable optimization algorithms. It was therefore clear that the art of constructing nondifferentiable optimization algorithms would have to be considerably extended if these algorithms are to become a realistic tool in engineering design. Professor E. Polak, in collaboration with Professor D. Q. Mayne of Imperial College, London, and Y. Wardi, a graduate student, have studied the possibility of obtaining nondifferentiable optimization algorithms by extension of differentiable optimization algorithms. Their results are most encouraging and are reported in:

E. Polak, D. Q. Mayne and Y. Wardi, "On the extension of constrained optimization algorithms from differentiable to nondifferentiable problems," University of California, Berkeley, Electronics Research Laboratory Memo No. UCBERL M81/78, 1981.

4. Professor A. Sangiovanni-Vincentelli has co-authored three survey papers dealing with various design aids for VLSI. These papers are as follows:

R. Newton, D. O. Pederson, A. Sangiovanni-Vincentelli and C. Sequin, "Design aids for VLSI: The Berkeley perspective," IEEE Trans. on Circuits and Systems, July 1981.

G. Hachtel and A. Sangiovanni-Vincentelli, "A survey of third generation simulation techniques," IEEE Proc., November 1981.

R. Brayton, G. Hachtel and A. Sangiovanni-Vincentelli, "A survey of optimization techniques for integrated circuit design," IEEE Proc., November 1981.

5. Professor A. Sangiovanni-Vincentelli and V. Visvanathan, a graduate student, partly in collaboration with Professor of R. Saeks of Texas Technological University, have made a considerable amount of progress in the area of diagnosability of nonlinear circuits and systems. Their work is reported in the following papers:

V. Visvanathan and A. Sangiovanni-Vincentelli, "Diagnosability of nonlinear circuits and systems, Part I: The DC case," Special joint issue of IEEE Trans. on Computer and IEEE Trans. on Circuits and Systems on Design for Testability, November 1981.

R. Saeks, A. Sangiovanni Vincentelli and V. Visvanathan, "Diagnosability of nonlinear circuits and systems-Part II: Dynamical systems," Special joint issue of IEEE Trans. on Computers and IEEE Trans. on Circuits and Systems, on Design for Testability, November 1981.

Significant Accomplishments

1. We have made important progress in devising superlinearly convergent algorithms for the solution of semi-infinite optimal design problems.

2. We have developed a comprehensive theory of diagnosability for dynamical nonlinear circuits and systems.

3. We have made a considerable amount of progress in developing DELIGHT, a highly sophisticated interactive computing system for optimization-based computer aided design of engineering systems and, in particular, of electronic circuits.

Proposed Research Program

Introduction

The research which we propose to carry out is in four parts, three of which must be kept highly co-ordinated, while the fourth one is rather independent of the others. The three coordinated parts of our research are: (i) the development of optimization algorithms for single and multi-objective optimization problems corresponding to electronic circuit design problems with simple inequality constraints, semi-infinite inequality constraints, and max min max ... type of constraints which results from specifications on nominal parameter values, frequency responses, tolerancing and trimming, etc.; (ii) the development of efficient simulation codes which compute not only responses but also various sensitivities and whose precision can be modulated as a means of controlling computing time; and (iii) the development of device and circuit models which allow to express system behavior in terms of a very small number of fundamental variables which can be controlled in the production process. The stand-alone part of our research is devoted to developing a comprehensive theory of fault diagnosis for nonlinear circuits and systems.

Our research results will be tested, evaluated and fine-tuned in our interactive computing facility which is currently being used to develop a multidisciplinary, optimization-based computer-aided design methodology. The power of the DEC 11/780 computer and the availability of sophisticated, interactive graphics features makes this facility an ideal medium for this type of experimental work.

Optimization Algorithms for Interactive Electronic Circuit Design.

a) Single-Objective Optimization

To accomodate most, if not all the important requirements of electronic circuit design, the optimization problem to be considered must be at least as complex as the following one

$$\min f(x) \mid g^i(x), i = 1, 2, \dots, I; \max_{w \in W} h^j(x, w) \leq 0, j = 1, 2, \dots, J;$$

$$\max_{e \in E} \max_{s \in S} \min_{t \in T} \max_{k \in K} z^k(x, e, s, t) \leq 0 \quad (1)$$

where f, g^i, h^j and z^k are all continuously differentiable and W, S, E, R , and $T \subset R^n$ are compact sets. At the present time, there are only two approaches possible to such a problem, one based on outer approximations of the constraint set and the other one on inner approximations of the constraint set [G6, P5, D16, S13].

(i) Outer approximations can be used to decompose (1) either into a sequence of nondifferentiable problems, as was done in [P6], or into a sequence of differentiable problems, as was done in [P5]. While, in general, it is preferable to decompose a difficult problem like (1) into an infinite sequence of differentiable problems, the price paid in [P5] for obtaining a sequence of differentiable problems was that these problems may have a very large and possibly ill conditioned set of constraints. Since our ability to handle nondifferentiable problems has considerably improved since [P5,P6] were written, we propose to examine the advantages of decomposing (1) into a sequence of nondifferentiable, but hopefully quite well conditioned problems. In particular, since the resulting nondifferentiable optimization problems have a very special structure, we hope to devise efficient algorithms for their solution.

(ii) Introduced for circuit design by Director and Hachtel [D16], inner approximations algorithms have made a very favorable initial impression on CAD users. Their main advantages are that they result in particularly simple subproblems and that whenever computation is suspended, the designer has at least a feasible design at his disposal. At present, their main disadvantages are that they only make sense for convex constraints and that there are no reasonable constraint dropping schemes to limit the growth of complexity of the resulting subproblems, which severely limits the precision with which they can solve a problem. Consequently, there remain a number of important unanswered questions. In particular, it is important to determine whether they can be extended to nonconvex problems and whether one can develop constraint dropping schemes that are as efficient as those proposed for outer approximations algorithms. We propose to address ourselves to these questions.

b) Multiobjective optimization

We have an ongoing effort in multiobjective optimization, which is used in electronic circuit design for performing trade-offs. There are a number characterizations of non-inferior (i.e. trade-off) point surfaces [C10,D2,M1,P3,P11]. Quite recently, we have obtained a number of interesting quantitative results on the efficient exploration of such surfaces [P8,P8a]. One of the major obstacles to the use of multiobjective optimization in design is the lack of meaningful methods of multidimensional information display. We propose to attack this problem in conjunction with developing efficient strategies for trade-off surface exploration.

Circuit Simulation

This part of the project is devoted to the development of simulation techniques and codes which are compatible with our optimization algorithms. The most urgent task is to extend at least one high quality simulation code so that it will yield the required derivatives. Since SPICE 2, which was developed at Berkeley, is such a code and since it already has some sensitivity computation features, such as for d.c. small-signal sensitivities, it is an ideal starting point for such a project. We note that some theoretical results for computing time domain sensitivities have already been obtained [D13], however, these results are not easily implemented within the context of existing

simulation programs, such as SPICE 2. Moreover, they promise to be very expensive in terms of computer time and storage requirements.

We therefore propose to develop and implement, as an extension of SPICE 2, an algorithm for time domain sensitivity analysis which makes use of a number of the intermediate computations, involving jacobians, required by the integration of the circuit equations.

Device Modeling

The major task in this area is to develop device models which lead to efficient computations in the context of optimization-based computer-aided design. In particular, emphasis will be placed on reducing the number of variables on which tolerances must be placed, since computing costs go up exponentially with this number. In particular, we shall attempt to develop appropriate models for complex MOS digital and analog circuits. The modeling process will be iterative, in that our new models will be tested experimentally against existing models and against actual circuit performance.

Fault Diagnosis of Nonlinear Circuits and Systems

Our results, reported in [V1], yield a necessary and sufficient condition for the diagnosability of nonlinear memoryless systems described by the equation:

$$y = f(u, a) \quad (2)$$

where $f(.,.)$ maps $R^p \times R^n$ into R^q . The condition involves a rank test on the matrix:

$$R_w(a) = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} [df(u, a)/da]^T [df(u, a)/da] w(u) du \quad (3)$$

where T denotes transpose and $w(.)$ is a continuous scalar valued function selected to ensure the existence of the integral.

As a further step, we studied the diagnosability of nonlinear dynamical circuits [S13]. Most such systems can be described by implicit algebraic-differential equations of the form

$$h(\dot{x}(t), x(t), y(t), u(t), a) = 0 \quad \text{for all } t \geq 0 \quad (4)$$

The theory and techniques developed for resistive circuits can be applied to this case by extending them to a function space setting. Among other things, this involves replacing the Jacobian and its transpose by the Frechet derivative and its adjoint. The difficulty in computing the Frechet derivative makes the above approach numerically very difficult. To deal with this complication, we propose to examine the possibility of replacing the original system by a discrete-time approximation, i.e., a discrete-time dynamical system of the form:

$$h(\dot{x}(t_n), x(t_n), y(t_n), u(t_n), a) = 0, \quad \text{for } n = 0, 1, 2, \dots \quad (5a)$$

$$\dot{x}(t_n) = \sum_{i=0}^k b_i x(t_{n-i}) \quad (5b)$$

The above form is of particular interest in electronic circuit design since the simulation of electronic circuits requires the solution of equations of the form (5a,5b) for a set of discrete time increments b_i as well as the time points t_{n-i} , which are chosen according to the particular backward differentiation formula used in the simulator. By using a discrete approximation to the continuous dynamical system, we will be able to couple algorithms for diagnosis with existing efficient simulators, such as SPICE 2. An additional important simplification in the diagnosis of systems of the form (4), will result from the fact that the Frechet derivative can be replaced by time-domain sensitivities which are much easier to compute.

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